

Instrumentation for ground vibration and earthquakes

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1. Recording earthquakes

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Earthquakes and man-made vibrations have very different causative mechanisms, but the seismographs used for recording in the near field are almost all of the "pendulum" class, which can all be described by a single equation of motion with two adjustable parameters. The fundamental distinctions between the two major classes of instrument reside almost entirely in the recording systems, in so far as earthquakes and unplanned explosions require continuous or automatically triggered recording, whereas vibration and planned explosions can be sampled at will. Variations in performance which can be built into this simple framework are discussed, and some introductory comments on later contributions to the Symposium are included.

INTRODUCTION

1. The classical method of studying earthquakes is by the codification of felt effects and the effect on buildings, which are graded numerically with the aid of formal "Intensity Scales". Such scales take into account variations in type of building, the available nature of human response under different circumstances, the graded effect of increasing building damage, sub-divided by type of structure and various forms of large-scale topographic effects which can be generated at high levels of intensity. The most modern scale used in Western countries is the 12-point "Modified Mercalli Scale" in which each point corresponds to about twice the acceleration or earth displacement of the point below. In Eastern countries, the Medvedjev Sponheuer and Karnik (MSK) Scale, producing an identical set of intensity levels adjusted to different specifications for types of structure, is more widely used.

2. When intensities have been determined throughout the region affected by an earthquake, the numbers can be contoured to produce an "iso-seismal map", an example of which is given in Fig. 1. The centre of the region of highest intensity on such a map is called the "epicentre" of the earthquake. An idea of the size or "magnitude" of the earthquake can be derived from the extent of the disturbed region. If the intensities rise to a very high level at the epicentre and decline rapidly with distance, the impression is that the earthquake waves have radiated from a source (called the "focus" or "hypocentre") which is comparatively close to the surface. Indications of deeper foci are obtained in the cases of earthquakes which are felt over wide areas, but in which the isoseismal banding is diffuse and does not rise to a high level at the epicentre. Studies of the type which have been described are sometimes improved in precision by the use of simple pendulums, called "seismoscopes", which make a permanent record of their displacement on a smoked

glass disc or other simple recording medium.

3. The next major contribution to the study of earthquake motion comes with the introduction of instruments which portray the movements as a function of time on a continuously moving recording surface. With such instruments the earthquake record (Fig. 2) can be seen to be divided into a number of "phases" originally described as Primary (P), Secondary (S) and Long (L) waves. These were identified as the compressional, transverse and surface waves predicted by elastic theory. By following the pattern of observable phases from one seismograph to another and plotting the times of arrival of each phase as a function of epicentral distance, travel-time tables were constructed and the observations were interpreted in terms of propagation paths through a spheroidal earth model. The sensitivity of modern seismographs is such that earthquakes below the threshold of damage can be detected in all parts of the world, including the most inaccessible regions. The pattern of occurrence, including major belts around the Pacific Ocean, and from the Alps through the Himalayas, together with the very narrow chains of epicentres forming under the oceans is strongly suggestive of an underlying cause (Fig. 3).

4. In the two decades preceeding the Second World War, schools of thought on world tectonics were divided between those who believed that the pattern was explicable in terms of a fixed crust collapsing over a cooling and shrinking interior as compared with those, led by Wegener, who believed that continents had originally been grouped in a single block (called Pangaea) which had broken up at the beginning of the Carboniferous period to produce the present pattern of land masses by the process known as "Continental Drift". The proponents of the shrinking earth attempted to measure total crustal shrinking by observing faulting and overthrusting in major mountain chains, and objected

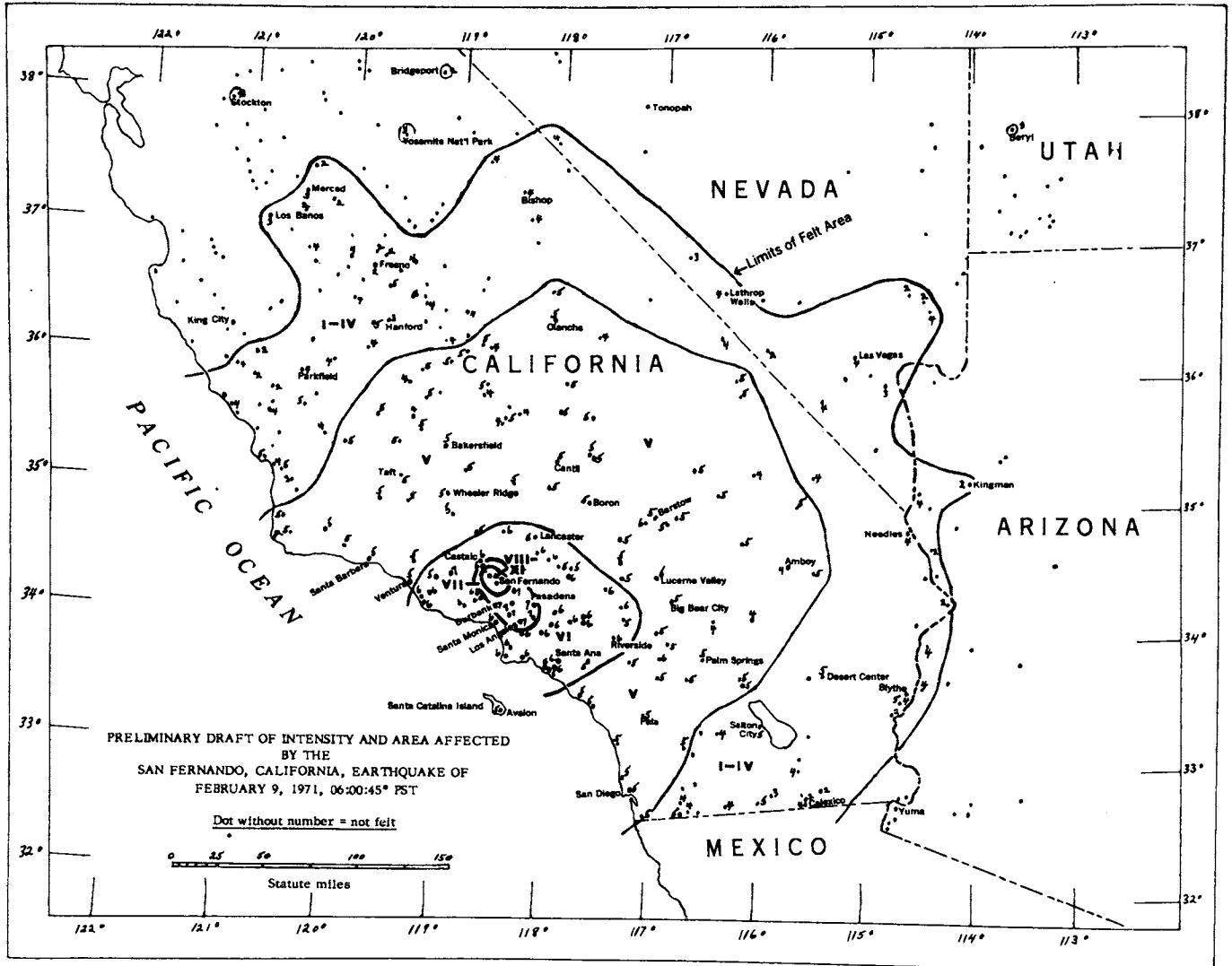


Fig.1. Draft isoseismal map of the San Fernando (California) earthquake of February 9, 1971 (Scott, 1971)

that continental drift could not be produced by any pattern of forces which could exist in a solid or quasi-solid earth. After the war, however, continental drift received striking confirmation by paleomagnetic evidence (which showed that the magnetisation directions of ancient rocks were indeed consistent with the concept of Gondwanaland) whereas more recent patterns enable the subsequent motions to be followed and showed that the continental ridges were the seats of crustal spreading. The precision of fit between continental shelves was shown to be even more precise than that claimed by Wegener. Major transcurrent faults were explained by differential sliding of plates, which could, in turn, be prompted either by the generation of new crust along ocean ridges or by the disappearance of crust in "subduction" zones or "collision" zones. In this way all of the major features of crustal movements were unified within the single pattern of "plate tectonics". (Fig. 4).

5. The power of the plate tectonic theory has, for the first time, given both seismologists and geologists means of understanding regional features of faulting and of earthquakes occurrence. We thus have a firm basis in which the estimation of seismic hazards can move forward from a purely statistical basis towards a strong combination of statistical extrapolation from historical occurrence with a causative understanding of earthquake distribution and mechanism. Dr Burton's talk on the assessment of seismic hazard will give an example of the way in which these theories are being applied in the United Kingdom. The lecture by Papatamatiou shows how the length of each instrumental catalogue could be extended by the utilisation of records from old instruments, thereby improving the basis for the statistical part of hazard assessment.

CLASSES OF INSTRUMENTS

6. All studies of earthquake motion or of earth vibration are aimed at detecting disturbances in the figure of the earth, in so far as the centre of gravity of the earth remains undisturbed in its orbital passage around the sun. These disturbances of figure can be detected by changes of stress (as with a pressure hydrophone) in strain (as with a bar, taut wire or Laser strain gauge) or acceleration (in which one measures the movement of a mass on a sprung mounting relative to the framework of the instrument). All of these methods can yield comparable levels of sensitivity and each has its place in the total field of seismometry. For mobile work on land, however, the advantages lie overwhelmingly with the mass-spring combination.

7. The basic descriptions of the earth-motion parameters which can be detected must not be confused with the types of "transducers" which can be used to detect the relative motions of the elements of pendulum or other seismographs. There are, for example, types of vibration sensors in which internal stresses of a system which is essentially a simple pendulum are

detected by means of resistive strain gauges or piezoelectric crystals. Such instruments are, in fact, measuring the response of the system to earth acceleration, rather than earth stress or earth strain. Equally, as we shall see below, the deflection of the suspended mass of a simple pendulum will be proportional, over various frequency ranges, to displacement, velocity or acceleration in the ground, although the forcing term in the equation of motion always simulates acceleration.

PERFORMANCE OF PENDULUM SEISMOGRAPHS

8. The essential configuration of the pendulum seismograph is shown in Fig. 5 where the system is represented as a mass on a hinged boom, whose free oscillations are damped out by a dashpot, and whose deflections are transmitted through a lever system or some more sophisticated combination of transducers and amplifiers to produce a permanent indication of boom deflection. The early Milne seismograph in the hall displays these features (except for the dashpot) in a simple and visible form.

9. The equation of motion of the simple pendulum is as follows:-

$$K \frac{d^2\phi}{dt^2} + D \frac{d\phi}{dt} + U\phi = -ML \frac{d^2x}{dt^2} \quad (1)$$

where K is the moment of inertia of the boom about its hinge, D is the moment of a damping force and U is the moment of the spring stiffness, all resulting from an angular deflection ϕ . The system behaves as though driven by a mass M responding to earth acceleration d^2x/dt^2 acting on the lever arm. Putting $U/K = \Omega_0^2$, $\beta = D/2k\Omega_0$ and $LM/K = 1/l$ yields the reduced equation of motion

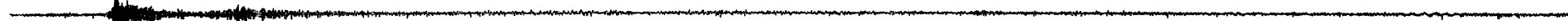
$$\frac{d^2\phi}{dt^2} + 2\beta\Omega_0 \frac{d\phi}{dt} + \Omega_0^2\phi = -\frac{1}{l} \frac{d^2x}{dt^2} \quad (2)$$

where 1/l is called the "reduced pendulum length". The case of a mass constrained to move along a fixed axis instead of swinging about a hinge can be reduced to the same form. The solution is

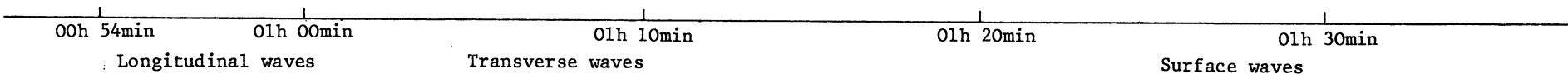
$$\phi = \frac{-\omega^2 X \cos(\omega t - \epsilon)}{1 \{ \Omega_0 [\Omega_0/\omega - \omega/\Omega_0]^2 + 4\beta^2 \}^{1/2}} \quad (3)$$

The solution can be represented by the single family of curves shown on Fig. 6.

10. The three versions of Fig. 6 show that the indicated output tends to an asymptote representing earth displacement when the frequency of earth motion is high compared with that of the resonant frequency of the system and tends to an asymptote representing earth acceleration at frequencies low compared with the system resonance. The portrayal of indicator deflections as a function of particle velocity in the earth shows a symmetrical form in which the peak of the response curve falls above or below the point of intersection of the asymptotes according as to whether the damping constant

Seismic
stationsRoyal Observatory Edinburgh
Short-period ZAuchinoon
Short-period ZBlack Hill
Short-period ZGalalaw
Short-period ZRoyal Observatory Edinburgh
Wide-band ZRoyal Observatory Edinburgh
Wide-band N-SRoyal Observatory Edinburgh
Wide-band E-W

Time code channel



The short-period channels yield the most precise timing for event location but the 3-component wide-band instrument collects a fuller record of the later phases

Fig.2. Short-period and wide-band recording of the Chile earthquake of November 30, 1976, recorded on the Scottish Lowlands Network (IGS)

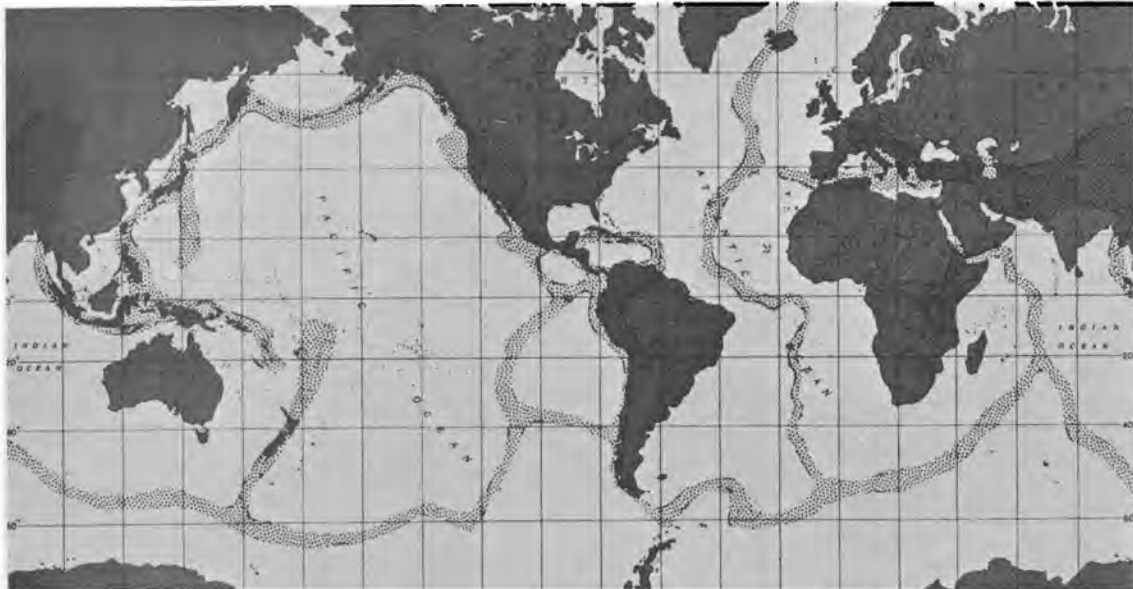


Fig.3. Seismically active regions of the world (USGS)

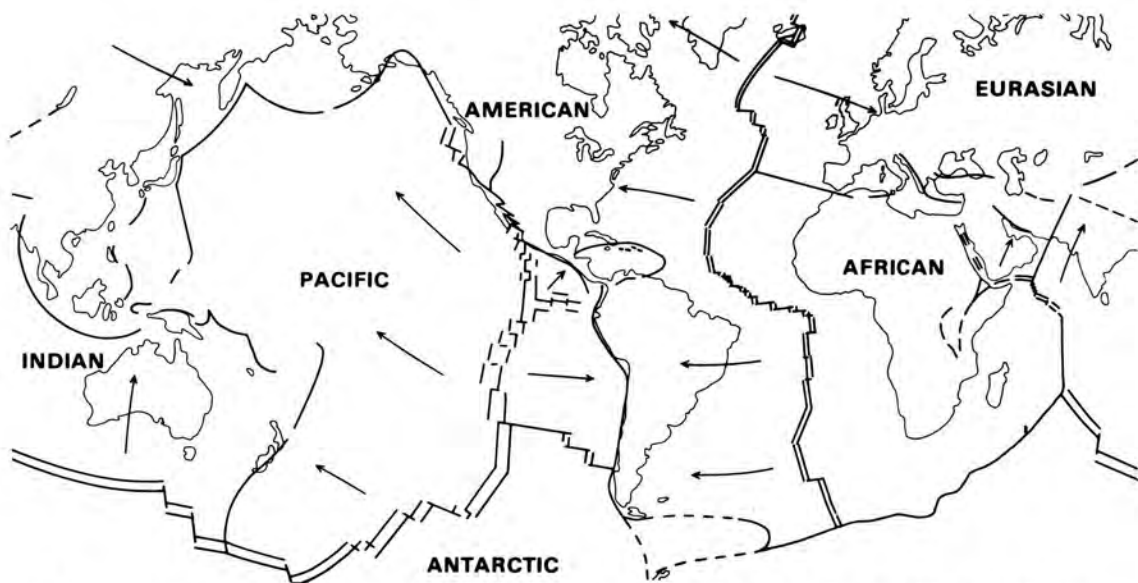


Fig.4. Boundaries of major continental and oceanic plates (after Bullard, 1971)

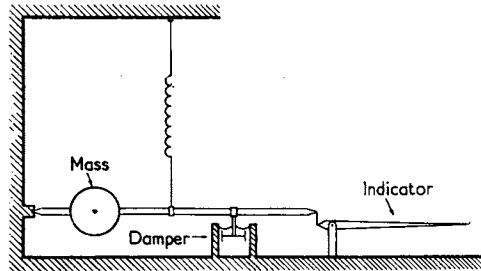


Fig.5. Essential features of the swinging-boom (pendulum) seismometer (Willmore, 1960)

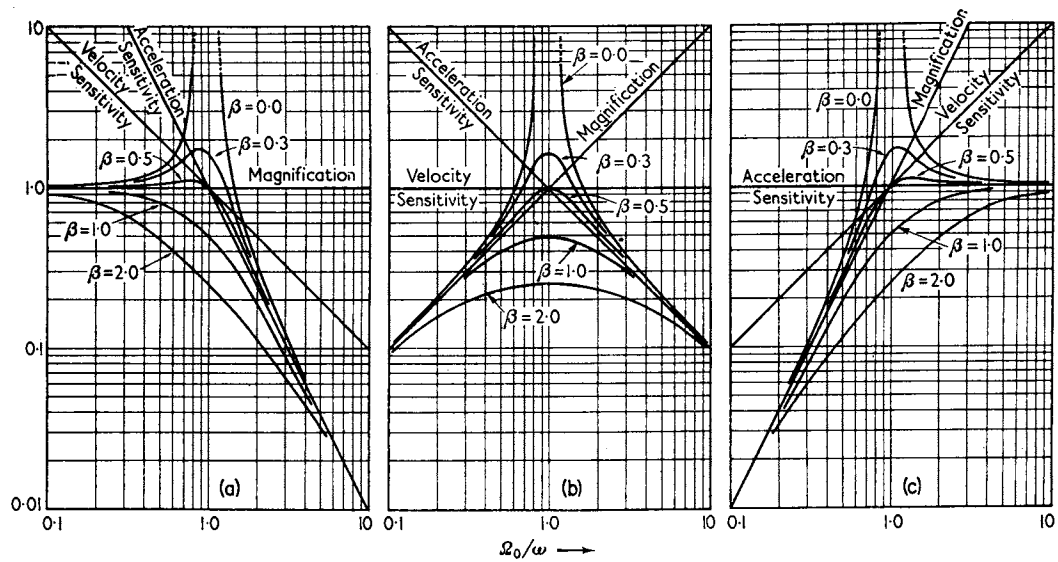


Fig.6. Frequency response of a simple pendulum as a function of displacement, velocity or acceleration in the ground (Willmore, 1960)

β is $>$ or $<$ 0.5. Over-damped systems have a flat response to earth velocity over a bandwidth of the order of $4\beta^2$. This symmetry in the resonant response of a simple pendulum is one reason why particle velocity is such a useful indicator of the effect of earth motion on structures, and it is a matter of some surprise that manufacturers have made so little use of this property of pendulums in the production of practical instruments.

11. The whole range of the response of simple pendulums can, in principle, be obtained by adjusting the mechanical constants in the equation of motion, but the use of electronic sensing devices provides the opportunity of making much larger changes by the introduction of electronic feedback. This is achieved by amplifying and shaping the output from a suitable transducer and converting this to a force on the suspended mass by passing an electric current through the auxiliary transducer. The following three cases are important:-

- i) The feedback force is made proportional to $d^2\phi/dt^2$, so the pendulum experiences enhanced resistance to angular acceleration of the mass, and the natural period is thereby depressed. Periods can, in practice, be extended by a factor of 20 or more, corresponding to virtual mass several hundred times greater than that which actually exists within the instrument.
- ii) The feedback force is made proportional to ϕ , so that negative feedback resists deflection of the boom, making the spring seem to be very stiff and the period very short. In such cases the feedback force simulates earth acceleration over a very wide range of frequency and the instrument known as the "force feedback accelerometer" emerges.
- iii) The feedback force is made proportional to $d\phi/dt$ so that feedback simulates damping. This system is particularly easy to apply to a seismometer fitted with a moving-coil transducer so that the ordinary damping system can be eliminated. As damping in such systems is commonly applied by shunting the output coil, there is the obvious advantage that the whole of the coil emf, instead of a reduced fraction of it, is available to drive the amplifier. A more subtle advantage comes from the fact that Brownian motion (or its electrical analogue, Johnson noise) arises entirely from dissipation within the system. Noise is therefore reduced when the dissipative elements are eliminated. The establishing of the response by negative feedback preserves the enhanced signal-noise ratio and the overall consequence is that quite small and light systems can be made to out-perform much larger systems based on traditional methods.

RECORDING SYSTEMS

12. One major division between the types of

recording systems lies between those in which the record moves continuously, as compared with those in which the record is automatically or manually switched on for short parts of the potential recording interval. Triggered recording eliminates much of the cost of recording material and the bulk of the recording system when the periods of interest form a small fraction of the total duration of potential observation, and thereby permit the acquisition of records with enhanced high-frequency content and dynamic range. Earthquakes and unplanned explosions do, however, present the problem that the recording system must be actuated in time to catch the first arrival of the event. Automatic systems which can perform this function in the presence of noise have to be quite sophisticated, typically incorporating short-term data stores to give time for the main storage system to run up to speed, and also require event recognition devices which are seldom as discriminatory as the eyes or ears of a skilled human observer. With extended networks the further problem exists that no one channel can be expected to record all events within the network area at the level of the response of the best or nearest channel. Automatic sensors therefore have to incorporate coincidence logic in addition to multi-channel sensing capability if all events are to be captured, and the overall complexity of this problem is preserving the independent role of the continuous recording system.

13. Within the classes of paragraph 12, practical systems include drum recording, visual strip recording, and analogue or digital recording on magnetic tape. The advantages and its disadvantages are as follows:-

i) Drum records. These (Fig. 7) provide very compact data storage, as the record is made in the form of a close spiral around a rotating drum. The example of Fig. 7 shows a small part of a record made on a drum rotating once in 15 minutes so that the small deflections on the lines represent the passage of 1 minute. The earthquake deflections can be recorded for many times the amplitude represented by the separation of succeeding turns, timing can be maintained to within a fraction of a second, and the absolute time of any minute mark can be recovered simply by counting along the line from a starting point and then across the record to arrive at a minute mark before or during an event of interest. The disadvantage of the system is that each component needs a separate drum so that multi-channel processing is very tedious.

ii) Visual strip recording. Multi-channel presentation on a visual strip provides for fairly easy comparison between channels but loses the simple ability to scan the full record at a glance and to identify time marks. End-to-end scanning by eye can be quite tedious in a long record, but the problem of time-mark identification can fairly easily be overcome by introducing digital coding or printed time identification.

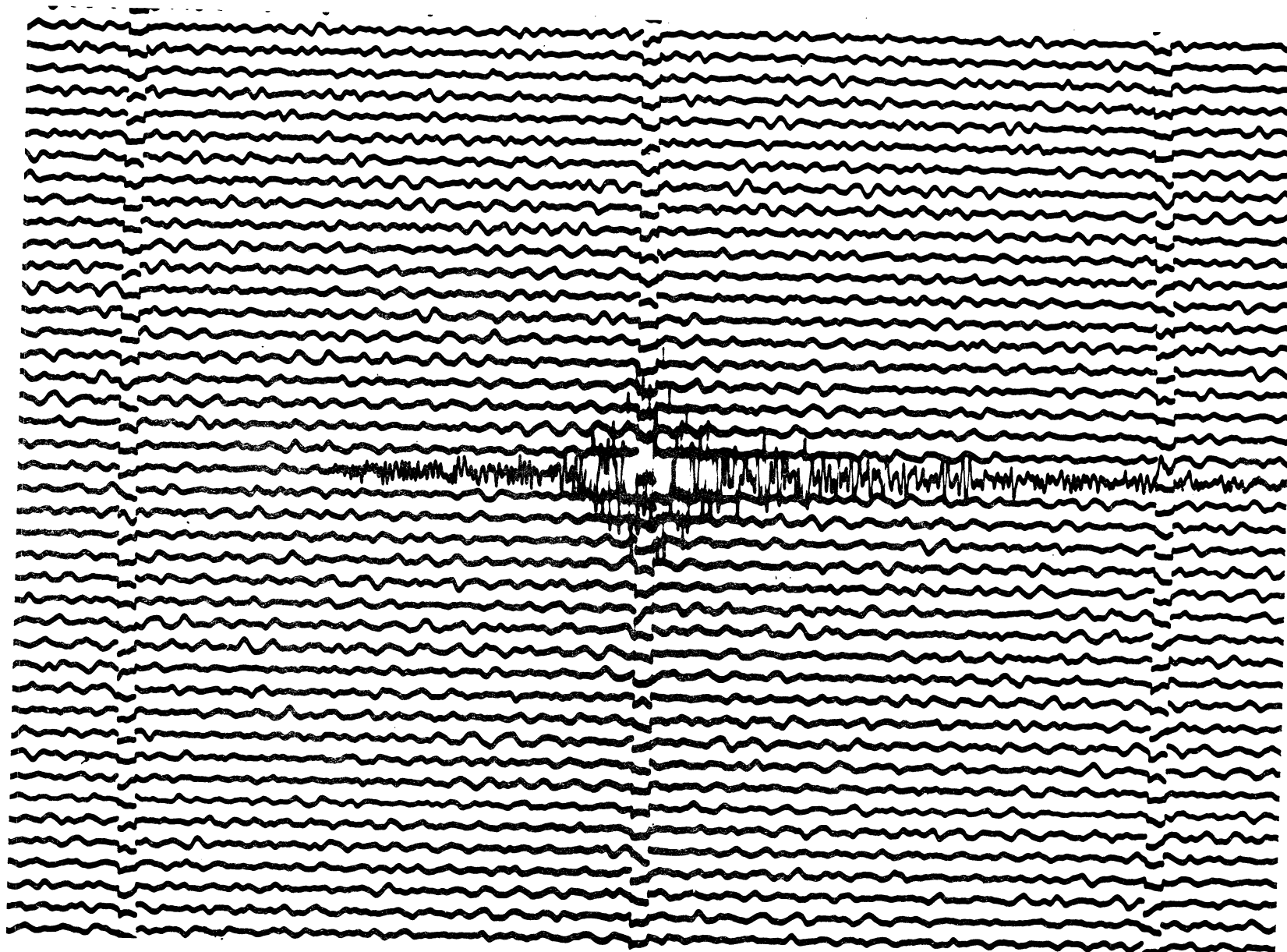


Fig.7. Portion of a short-period seismograph record, showing the close packing of data obtained by drum recording (IGS)



Fig.8. Portable magnetic-tape recorder, providing 11 tracks of seismic data, plus time and flutter control, on half-inch tape (Racal-Thermionic)

iii) Analogue or digital tape recording. These systems open the whole field of sophisticated record processing by means of computers. Analogue tape recording is much more economical in volume of tape for given frequency content and offers the opportunity of accelerated audio-visual search if records are played back at the speed required to transpose seismic signals into the range of audibility for a human observer. For teleseismic records, speed-up ratios as high as 240:1 can be used. Digital recording gives maximum integrity of data and a maximum interchangeability of records in standard format between electronic computers. Recording costs are, however, considerably higher. An event search in a computer takes longer than a comparable search by trained operators.

14. Fig. 8 shows a modern tape recorder which has a total data capability, when placed at the centre of a telemetered network, comparable to that of a national network of seismograph stations of two decades ago. The power consumption of the illustrated recorder is 2 watts. Telemetered outstations can be powered from batteries at a level of about 1 watt per station, so that extended networks can easily be assembled and maintained.

EARTHQUAKE VERSUS VIBRATION RECORDING

15. Given that all simple pendulums are reducible to a single equation of motion, we see that the distinction between earthquake and vibration recording reduces to matters of detail in the design of the instrumentation and to the fact that the earthquakes are unexpected, whereas humanly generated sources can often be anticipated or produce continuous signals which can be sampled at will. Thus, vibration instruments are typically switched or triggered to give maximum frequency resolution whereas continuous recording has a much greater place in earthquake studies.

16. The final distinction comes in dynamic range. In quiet locations ground motions as low as $10^{-9}m$ or accelerations as low as $10^{-9}g$ are detectable whereas motions in the epicentre

of destructive earthquakes can exceed displacements of one metre or acceleration of $1g$. Vibration sensing, on the other hand, is seldom of interest at levels of much less than one thousandth of those which are destructive or otherwise totally unacceptable. Total recording of earthquakes therefore requires a dynamic range of some 180db requiring suites of instrumentation for total cover. Vibration systems, on the other hand, are such that a single instrument can cover the whole range of levels to be expected within the area of any specialist interest.

CONCLUSION

17. We have shown how the single concept of the simple pendulum can be combined with recording systems to cover a wide range of human requirements and our study must move on from this point to the techniques of interpretation and utilisation of data. On the earthquake side we shall hear Drs Browitt and Long talking about methods of deployment of instrumental networks, and examples of case histories of particular cases by Westbrook and Stenling. The exhibit room contains many examples of the classes of instruments which have been mentioned.

ACKNOWLEDGEMENT

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2. Ground vibration instrumentation — a general review

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Man made ground vibration affects the serviceability of structures and human comfort. Depending upon the source and transmission path, ground vibration may approximate to a variety of idealised forms ranging from simple sinusoidal periodic motion to non-stationary random motion, calling for progressively more sophisticated measuring and analytical methods. The measurements are usually used with reference to empirically based criteria for thresholds of building damage and/or human discomfort. The thresholds for building damage for impulsive, short duration loadings are in dispute but it is being recognized that some statistical description of damage is desirable. The description of a ground vibration in the frequency domain may permit better single parameter damage relationships to be established. Methods are now available to estimate structural response but need proper description of the ground motion in three components.

GROUND VIBRATION

INTRODUCTION

1) It is the intention in this paper to review the purpose of and methods for the measurement and evaluation of the ground vibrations, (excluding earthquakes) which are of concern to engineers and environmentalists. These are almost exclusively generated by man and infringe upon the environment affecting the serviceability of his structures and services and the comfort and well being of his person. Rarely are these vibrations dramatically destructive.

2) Measurements are usually motivated by a need to control and indeed restrict the vibration generated by some human activity in accordance to empirical or analytically based criteria. The instrumentation adopted tends therefore towards that providing the simplest information sufficient to properly characterise the vibration, usually in terms of some quantity accepted as a criterion of damage or comfort.

3) This review deals then with the types of ground vibration which may be encountered and the data required to characterise them.

SOURCES OF GROUND VIBRATION

4) Natural ground vibrations excluding earthquakes may arise from the following:

- (a) long period movement such as earth tides
- (b) sea wave induced micro seismicity
- (c) barometric fluctuations
- (d) running water
- (e) rock slides

(f) wind, vegetation and structure coupled

5) Sources (a) to (c) are of generally longer periods $T > 1$ seconds but sources (c) may give shorter period disturbances $T < 0.1$ seconds. The levels are usually so small as to be only of concern to engineers when dealing with the most sensitive of installations (laser beds, synchrotron magnet columns, "very quiet laboratories").

6) Man made ground vibrations can be grouped as arising from:

(a) cyclic out of balance forces and torques coupled from reciprocating or rotating machinery via their foundations to the ground.

(b) impact generated vibrations such as may arise from forging hammers, piling, demolition.

(c) Explosion generated vibrations from both small and large sources.

(d) pulse forces from discharges of capacitances, sudden loads on generators.

(e) combined impact generated and out of balance sources such as generated by road and rail traffic.

(f) air noise/ground to structure coupled vibrations.

(g) aircraft jet impingement on take off and landing.

(h) flow induced noise; water generated - sluices etc. Boilers, furnaces coupled through foundations.

TABLE I

SOURCE	TYPE OF VIBRATION	REQUIRED INFORMATION
Pile Vibrator	Periodic harmonic	Period or frequency and a magnitude of signal, band width can be restricted.
Reciprocating engine	Periodic non harmonic	Period or frequency and signal magnitude over extended time, band width can be restricted.
Dense traffic	{ Stationary Random } { Non Stationary Random }	Power of signal in infinitely narrow frequency band, given centre frequency over infinitely long time. System requires wide band width.
Explosion (near/middle field)		
Impact, Explosions, near field	Shock, Transient	Exact time history in terms of force, acceleration, velocity or displacement. Fourier spectrum. System requires wide band width, and dynamic range.

TYPES OF VIBRATION

7) A vibration process requires certain minimum information to fully describe it, depending on whether it is periodic harmonic, periodic complex, stationary random, shock transient, or non-stationary random. Broch 1972, Ref : 1
 Periodic harmonic (continuous)

8) Periodic vibrations with single period are fully described by a period (T) or frequency (f) and a magnitude which may be the amplitude of displacement (u), velocity (u-dot), or acceleration (u-double-dot). A description based upon the peak values of these quantities relates only to instantaneous conditions. Time history for one cycle is included in the description if one uses the absolute average amplitude, or the Root Mean Square (RMS) amplitude.

Periodic complex (continuous)

9) Periodic complex vibrations consist of a number of discrete sinusoidal vibrations. They may be separated and a spectrum drawn up in which the different frequencies appear as discrete lines. This kind of vibration is commonly encountered especially from reciprocating machinery.

Periodic non-continuous

10) The short duration motion with apparently periodic form contains the starting transient and cannot be fully described as a continuous vibration.

Stationary random

11) Many vibrations encountered can be regarded as having random characteristics, that is individual particle motions are never exactly repeated even if one measures over an infinite duration. To describe such vibrations we must use probabilistic terms. The most commonly used is the 'probability density':

$$p_u = \lim_{\Delta u \rightarrow 0} \frac{P(u) - P(u + \Delta u)}{\Delta u}$$

Here p(u) is the probability density, P(u) the probability that an instantaneous amplitude exceeds u, and P(u + Δu) is the probability of occurrence of instantaneous amplitude values exceeding u + Δu. All values of p(u) for all values of u when plotted give a 'probability density curve' which when integrated between two values of u₂ and u₁, gives the probability of occurrence of instantaneous amplitude values between interval u₂ - u₁.

12) Probability density describes an 'instantaneous' condition. In order to bring time history and frequency content into the description, the 'auto-correlation' function is used (see Robson 1963 for definitions, Ref: 2)

$$\psi_r = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f(t+r) dt$$

From this function may be derived the 'mean square spectral density' function, W(f) when

$$\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f^2(t) dt = \int_0^\infty W(f) df$$

The left hand side measures power in the process in time terms and the right hand side in frequency terms. This equation may be presented in the form

$$W(f) = \lim_{B \rightarrow \infty} \lim_{T \rightarrow 0} \frac{1}{BT} \int_0^T u_B^2(f,t) dt$$

describing that part of average power of the signal function u(t) contained in an infinitely narrow frequency band B with centre frequency f, averaged over an infinitely long time. In practice B and T are finite but their choice will not be dealt with here. It is this function which is usually obtained by direct spectral analysis from a vibration record.

Shock and transient

13) Shock is the transfer of kinetic energy to a system in a time short compared with the natural period of that system. Shock can be described by a Fourier transform

$$F(f) = \int_{-\infty}^{+\infty} F(t) e^{-j\omega t} dt$$

Although such Fourier integrals are necessary for a full description, the peak response of a single degree of freedom system is usually used in assessing the effects of a particular shock and in describing 'strong motion' earthquakes.

14) For transient phenomena, the duration of the input may be several times the natural frequency of the system excited. There may be a single period or an oscillation.

Non-stationary random

15) All stationary random vibrations in practice are non-stationary because their statistical properties change with time. The theoretical analysis of non-stationary random vibrations is difficult and requires vast amounts of data. Some kind of time averaging is usually used and this means that measuring equipment must have response and averaging times short compared with trends in the non-stationary random data.

EXAMPLES OF GROUND VIBRATION

16) Vibration may be classified in order of increasing information required to describe it, in a progression; continuous periodic harmonic, continuous periodic complex in periodic non-continuous stationary random, shock and transient, non-stationary random.

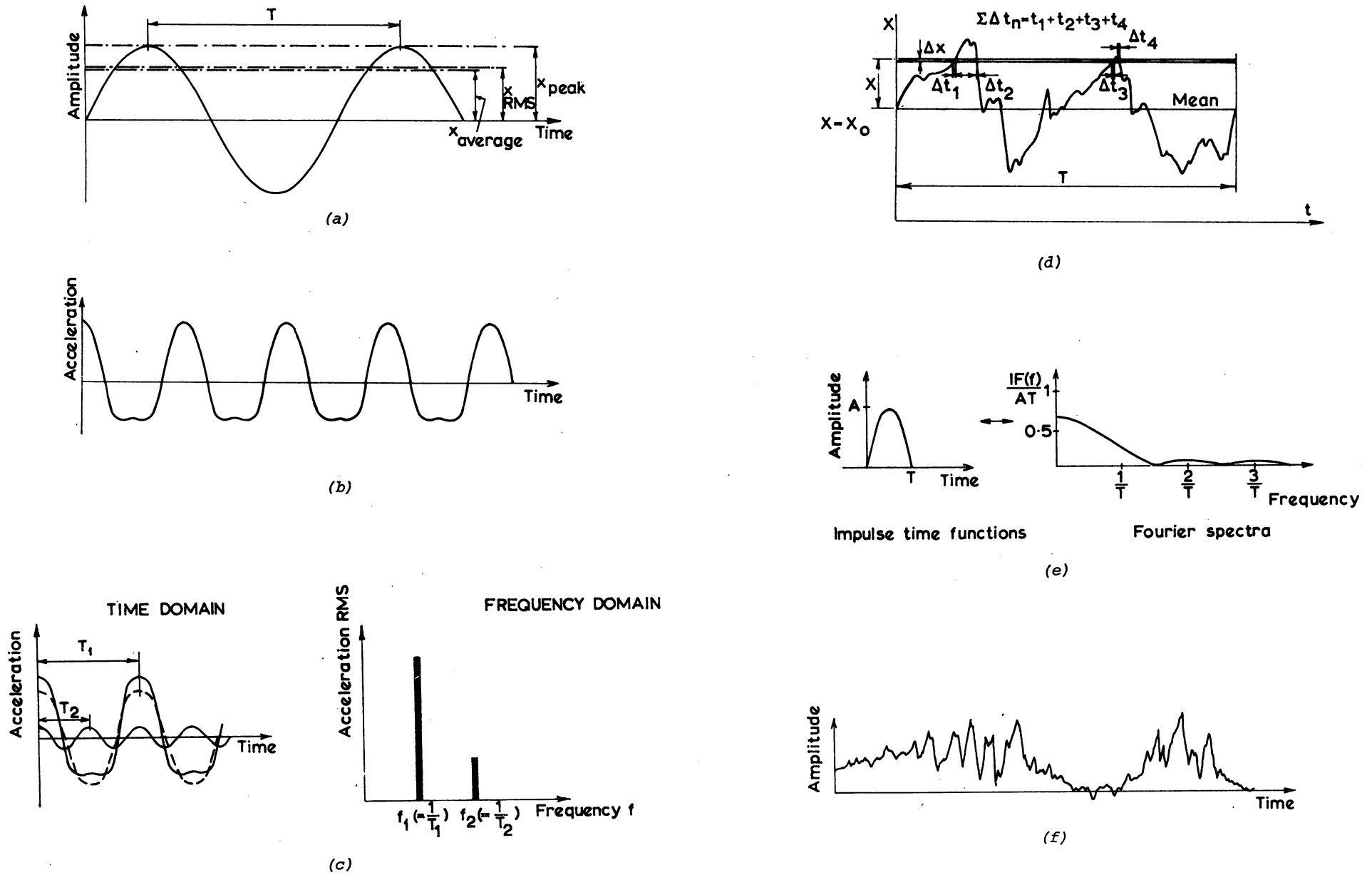


Fig.1. Types of vibration (after Broch): (a) pure harmonic sinusoidal continuous signal; peak, RMS and average absolute value indicated; (b) non-harmonic periodic motion; (c) non-harmonic signal in time and frequency domain; (d) probability and probability density concepts; (e) half sine shock pulse in time and frequency domains; (F) non-stationary random vibration

- 17) In Table I vibrations from man made sources have had assigned to them their characteristic type of vibration. It should be noted that the character of many transient and random vibrations in passage through the upper ground layers is altered and appears as a single periodic harmonic ground motion.
- 18) A vibration may be described in two ways, as the displacement, velocity or acceleration versus time (in the 'time domain') or as the displacement, velocity or acceleration in a very small interval of frequency (frequency spectrum, in the 'frequency domain').
- 19) The two ways are interchangeable i.e. a time history can be recovered from a frequency spectrum. Some examples of typical vibration signals in both domains are given in Fig. 1 and in Fig. 2 examples are given of ground vibration from a variety of sources.
- 20) The ground vibration from a vibratory compacting roller (Fig. 2a) is seen to be of complex periodic type with a dominant frequency. It can adequately be described by a system which performs without distorting amplitude and phase over a limited frequency range. Vibration levels to be expected from rotating machines can be deduced from ISO.2373 'Mechanical vibration of certain rotating machinery with shaft heights of between 80-400mm - Measurement and Evaluation of Vibration Severity.
- 21) The vibrations generated by road and rail traffic are under intensive study (Whiffen et al 1971 Ref. 3, Lande 1974 Ref. 4). The record from a single vehicle (Fig. 2b) shows quasi-periodic features. Lande has shown a broad frequency band with components determined by the vehicles suspension characteristics. It has also been suggested that at speeds greater than 35 km/h most of the vibration is of a Rayleigh wave type (see later).
- 22) Two types of piling are in current use: impact and vibratory. Impact piling energies range from 10^4 J to 5×10^5 J and vibratory systems have energies ranging from 10^3 J/cycle to 5×10^5 J/cycle with frequencies around 30-60 Hz in the most frequently used types to several hundred Hz for the so called 'sonic' pile. In Fig. 2c some examples are given. Attewell & Farmer 1973 Ref. 5 have studied the attenuation of piling vibration and described the particle motions induced by impact driving.
- 23) The ground motion of Fig. 2d is from a distant large quarry blast. The signal content can be divided into two parts, the first with predominantly higher frequency and a random appearance and the record apparently of a quasi-periodic form. It was shown for signals of the type that a 4.5 Hz critically damped geophone system was reasonably adequate. Integrating a digitised acceleration time record of the same event recorded by a piezo-accelerometer gave a record with almost identical peak particle velocities. A similar agreement between an integrated acceleration record and a geophone record was found when measuring the ground response to aircraft jet noise on take-off (Fig. 2e). In both cases (Fig. 2c and Fig. 2e) the low frequency content (< 6 Hz) was small. The frequency content of other kinds of jet induced ground vibrations has been described by Heller 1967 Ref. 6. They can contain low frequencies.
- 24) Similar occurrence was not achieved when comparing the results from a strong motion accelerograph measuring alongside a geophone near (15 m) to the point of impact of cooling tower (Skipp et al 1972 Ref. 7). The low frequencies (< 5 Hz) were significant (see Fig. 3).
- 25) In order to adequately describe the different types of vibration, a variety of instrumentation capacity is required. For a continuous periodic harmonic motion a peak value of signal magnitude and frequency or an RMS level are needed. The sensor should have a calibrated linear response in the region of the measured frequency. If the vibrations are continuous periodic, non harmonic, the time history of signal magnitude is needed in a form from which the harmonic components can be extracted and with a system linear in response to signal magnitude and phase over the frequency ranges of the components.
- 26) If motion is not continuous, then the vibration cannot be so simply defined. The 'starting transient' includes low frequencies and although the record may appear harmonic, unless such transients can be neglected in a long record length the vibration needs more complex definition. In general non continuous vibrations need descriptions in the frequency domain. Analysis is easier by digital filtering but care must be taken to select suitably weighted filters. Fig. 2f.
- 27) When dealing with stationary random vibration ideally a system should respond linearly in amplitude and phase to frequencies of zero to infinity and record the time history of motion.
- 28) Phase distortion is especially troublesome when one is looking for peak amplitudes and is especially so for transient signals. The use of RMS is often preferred and for periodic continuous and complex signals does reduce the problem but for non-stationary random motion the forming of an RMS is not easy. Many of these problems are dealt with in standard text books and reference volumes (Harris & Crede 1961 Ref.8).
- 29) Man made vibrations of concern to engineering range from a few mm/s to several hundred mm/s, from a few hertz to several hundred hertz, from simple periodic continuous motion to non stationary random motion. It is not surprising that no single instrumentation system can cope with all these demands. When simplifications are being made it is however important to ensure that the resulting representation of the true ground signal is adequate.
- 30) There is an increasing tendency to describe

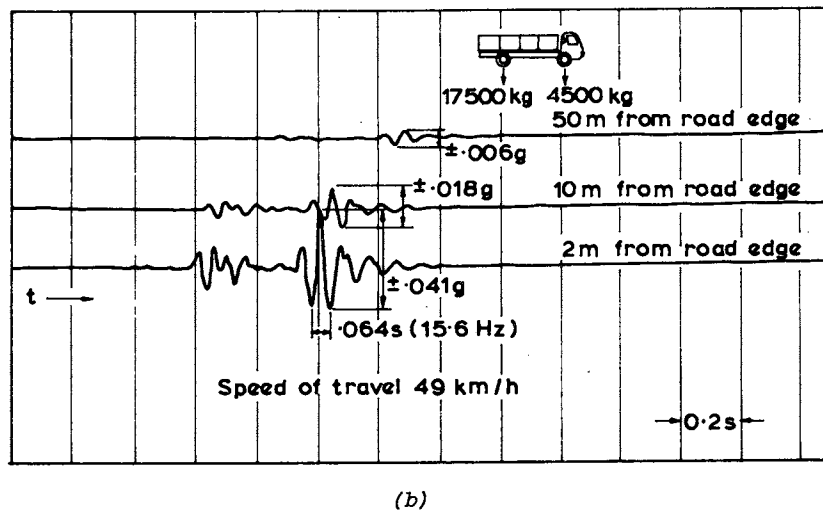
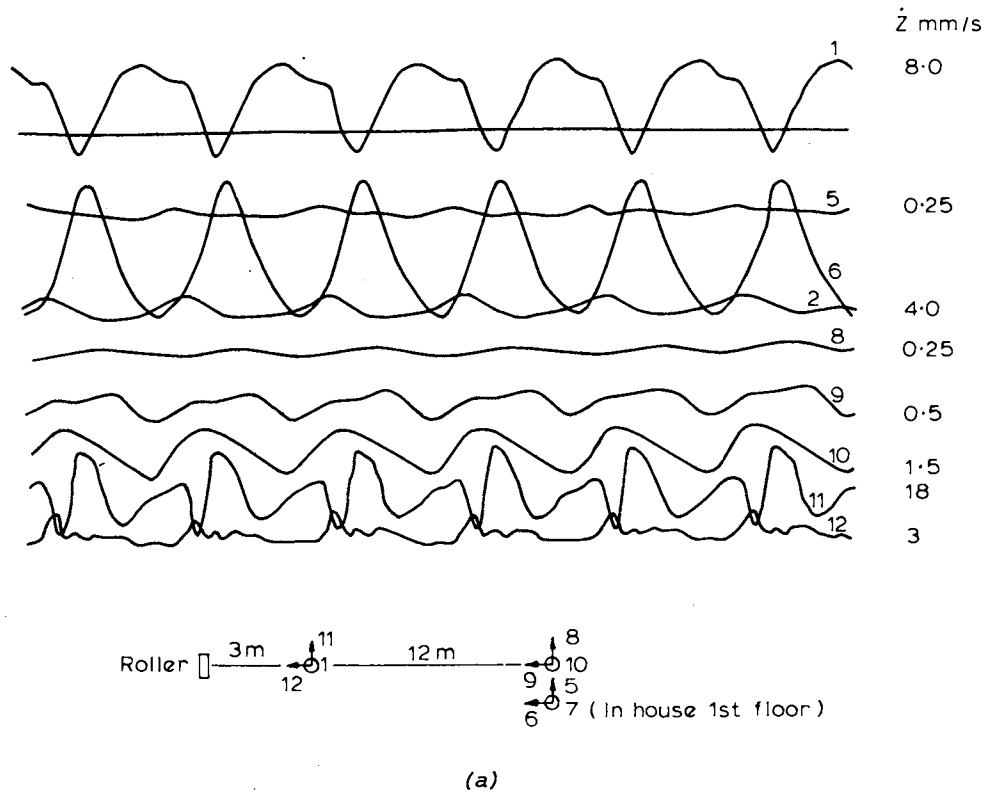
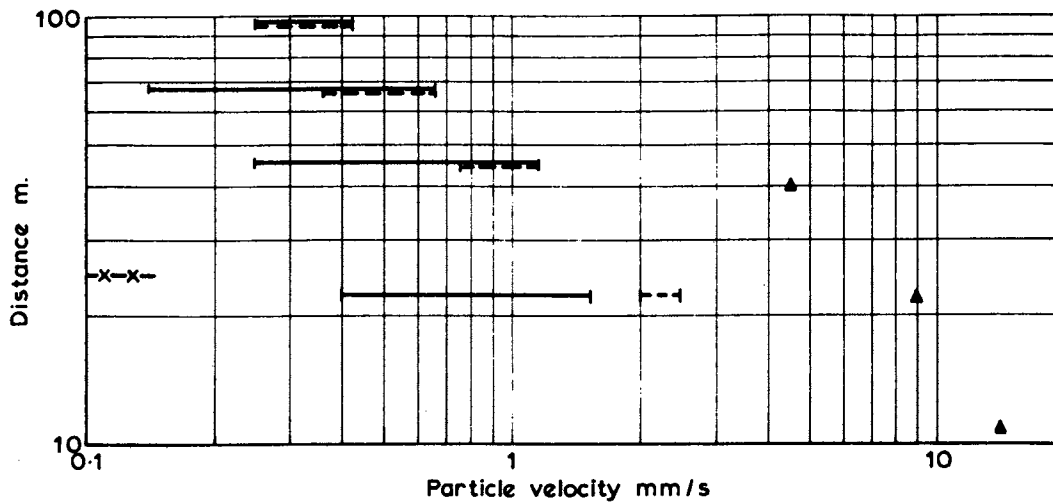


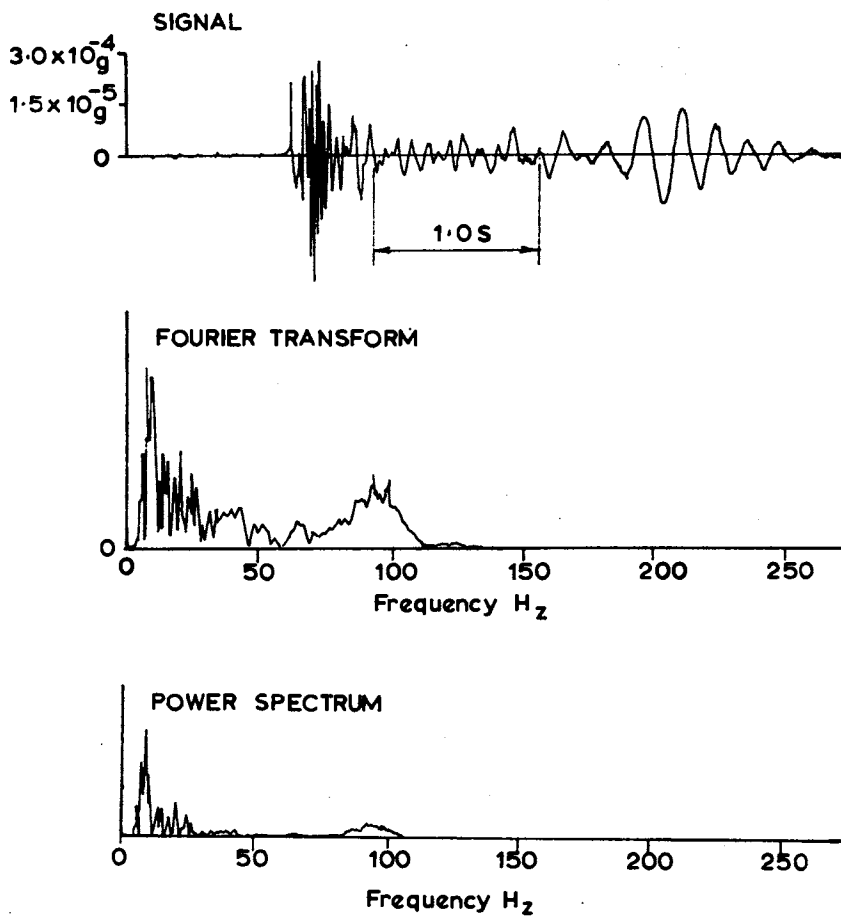
Fig.2. Ground vibration: (a) from vibratory roller; (b) from traffic - truck over 38 mm x 230 mm plank (after Whiffin); contd



KEY

- M26 Vibrator, sheet piles, dense gravel
- Delmeg 16 diesel hammer, sheet piles, dense gravel
- x-x- M26 1m casing driving London Clay
- ▲ 36,000 j hammer (Attwell)

(c)



(d)

Fig.2. (contd). Ground vibration: (c) from piling; (d) from quarry blasting; contd

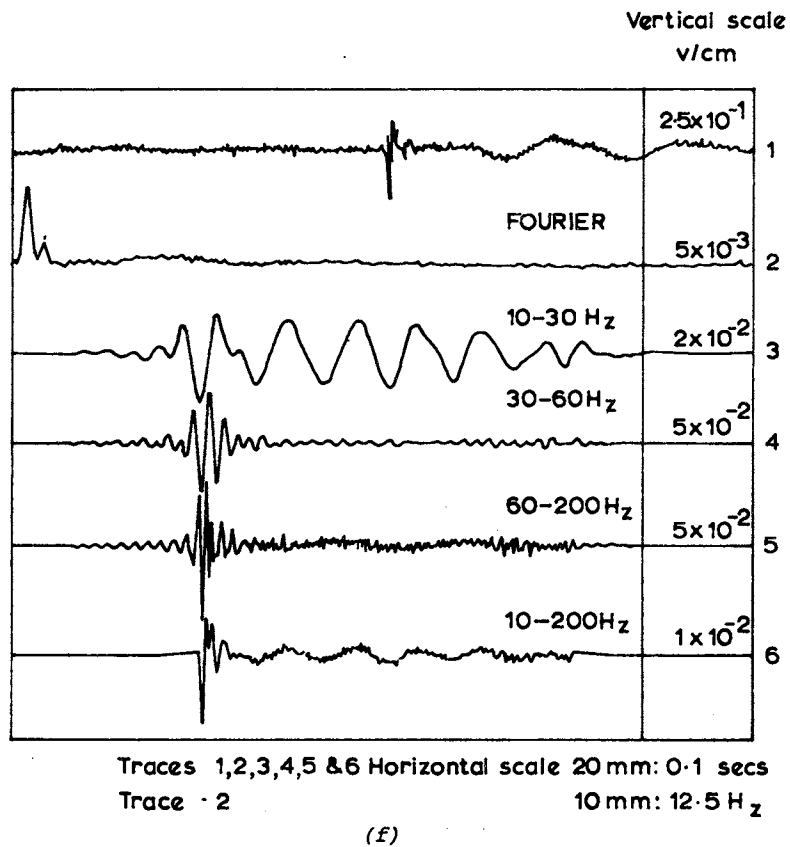
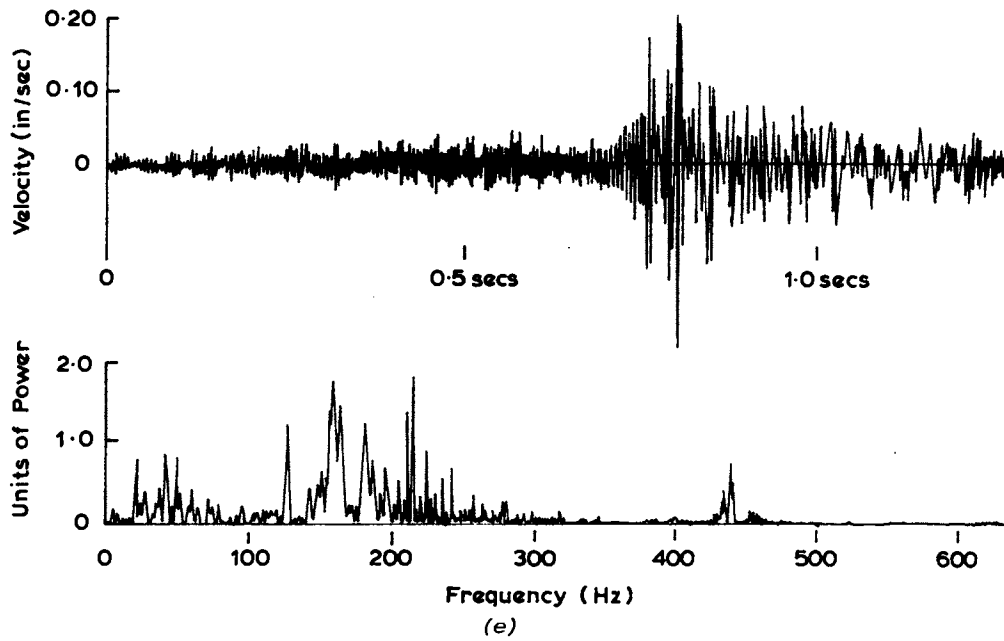


Fig.2 (contd). Ground vibration: (e) from jet, 0.5 m below runway - Concorde take-off; (f) from explosives in saturated sands

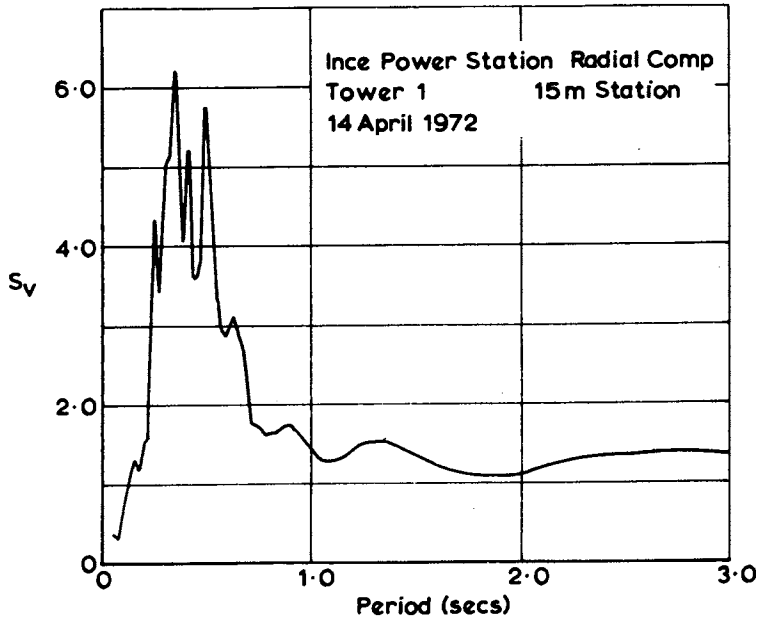
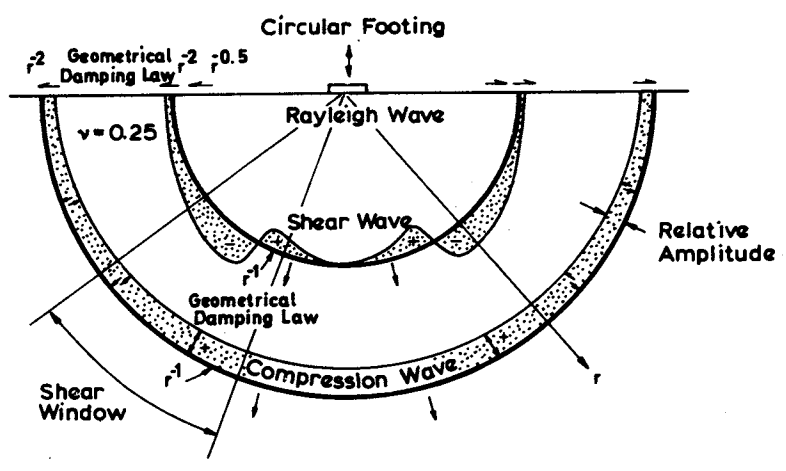
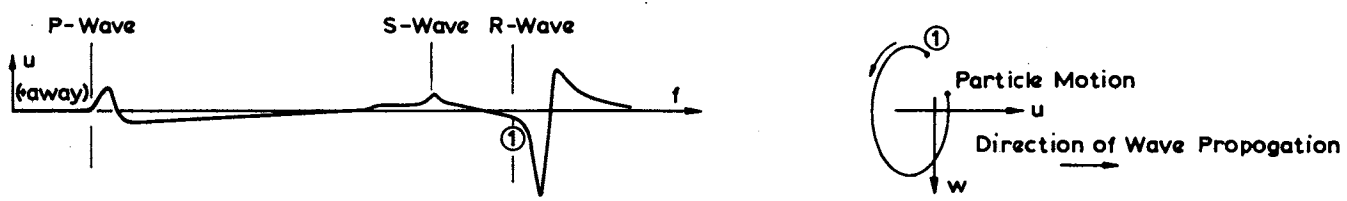


Fig.3. Response spectrum, impact of cooling tower on soft ground



Wave Type	Per Cent of Total Energy
Rayleigh	67
Shear	26
Compression	7

Fig.4. Point and distributed load on surface of an elastic half space (after Richart)

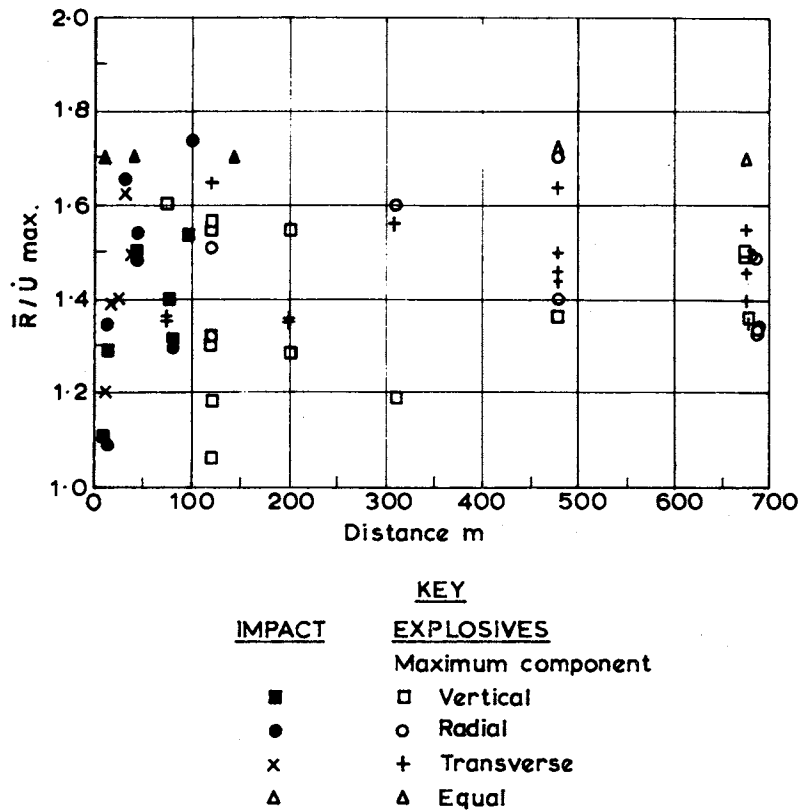


Fig.5. Relationship between maximum component and peak resultant ($R^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2$)

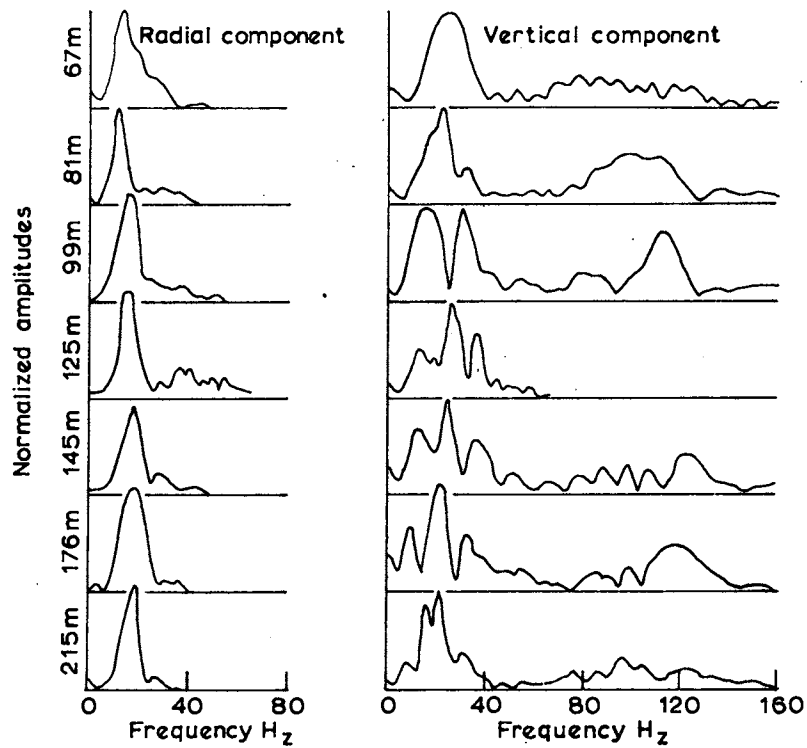


Fig.6. Frequency spectrum of blast signal and distance (Peter Nicholls)

and operate with signals in the frequency rather than the time domain, and to use the signals in calculating via various models, the 'full' response of a structure. Great care must then be taken to make sure that the vibration record is a faithful representation of ground motion. This calls for a recognition that the instrumentation system should have suitable frequency coverage (band width), dynamic range and sensitivity. (see McEvilly 1976 Ref.9).

PROPAGATION OF GROUND VIBRATION

31) The propagation of elastic waves in stratified ground is a complex subject. It must be touched upon because the engineer is interested in the relationship between the magnitude of ground vibration at a point and its distance from a source, and the way the character of the vibration is affected in transmission. These concerns may be broken down into three aspects:

- (a) Relationship between a peak signal magnitude any distance from source.
- (b) Relationship between component of motion in different directions and distance from source.
- (c) Changes in frequency content and distance from source.

32) When an oscillatory or impulsive force is applied to an elastic medium elastic energy may be carried away by different types of elastic wave. The proportions carried by different types of wave depend upon the source mechanism. The source mechanisms for various situations can be idealised as follows:

33) (a) Cyclic or impulsive load on an area of a semi-infinite elastic medium. (b) Moving point load on the surface of an elastic half space. (c) Expansion of a spherical cavity in elasto-plastic medium. (Lamb 1904 Ref. 10, Miller and Pursey 1954 Ref. 11, O'Brien 1969 Ref. 12).

Corresponding examples are given as follows:

- (a) Machine foundations. Impact from demolition
- (b) Surface gas explosions, sonic boom, air/ground coupled vibration.
- (c) Buried explosive sources.

34) For each of these idealisations it is possible to define the proportion of energy radiated by different types of elastic waves.

35) A useful example is that of the energy radiated from a vertically cyclic loaded circular area on a homogeneous isotropic elastic medium where 67% is radiated as Rayleigh waves, 26% as shear waves, 7% as P (compressional) waves, each wave being propagated with different velocity.

36) The Rayleigh (R) wave attenuates with distance by geometrical spreading such that its peak signal magnitude decreases as $1/r$, the shear wave (Fig. 4) attenuates with distance as $1/r$ and the P wave attenuates as $1/r$. These

components at the surface attenuate however as $1/r^2$. Such relationships hold when the distance is so far away that the source can be regarded as a 'point' (2.5λ) (λ is the wavelength of the R wave). Close to the source, interference between motion generated over a surface of contact complicates the picture.

37) Other source mechanisms give rise to different proportions of energy carried away by the various types of elastic wave. For a simple periodic motion the energy per unit area of a plane wave front per wave length is proportional to the square of displacement (Bullen Ref. 13). In Fig. 5 an example is given showing the relationship between the peak single component and a peak 'vector' envelope for quarry blasting and demolition impact. It shows how it is not possible in many cases to predict in which direction the maximum motion will occur.

38) It can be seen then that for near surface sources which can be idealised as a cyclic vertical load Rayleigh waves will tend to predominate. This would suggest peak signal magnitudes in a vertical and radial sense (from source). In practice however there is often conversion of one kind of wave to another at discontinuities in the ground. Vibrations of engineering significance are often measured at such close distance from the source that the different wave types have not 'separated' and the source does not approximate to a point.

39) Not only are amplitudes and component relationships changed with distance from a source but so is the frequency content. High frequencies tend to attenuate (Fig. 6) but there are instances where energy refracted or channelled in a particular stratum gives rise to higher frequency vibrations sometimes at great distances.

40) The attenuation of peak ground motion with distance may be expressed in terms of a scaled distance $R/(E)^n$ for the different source 'magnitude' and examples are given on Fig. 7 and 8.

41) The most appropriate value of 'n' has been a subject of some dispute. It is common practice in USA to scale to $n = 1/2$ although for fully contained spherical sources $n = 1/3$ is dimensionally correct (Ambraseys and Hendron 1968 Ref. 12). Ball 1976 Ref. 15 has suggested that correlation coefficients between scaled distance and vibration amplitude of between 0.75 over 0.8 are reasonable. In this range the difference between $n = 1/2$ and $n = 1/3$ scaling is often negligible.

42) Typical P wave velocities in soils and rocks range from 1000 - 5000 m/s and R and S wave velocities from 200 - 2000 m/s. At 5 - 50 Hz we are dealing with P waves of wave lengths 20 to 1000 m and R and S waves of 4 to 400. For many situations the R wave carries most energy and many of our problems are within a few hundred metres of a source so by the 2.5 criterion (Richart et al 1970 Ref. 16) separate

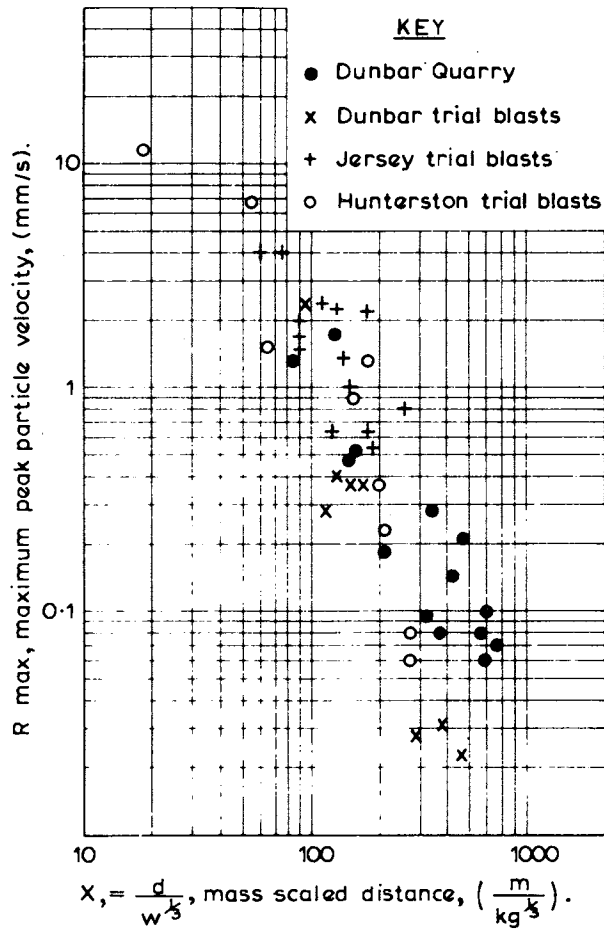


Fig.7. Scaled distance relationship - explosives

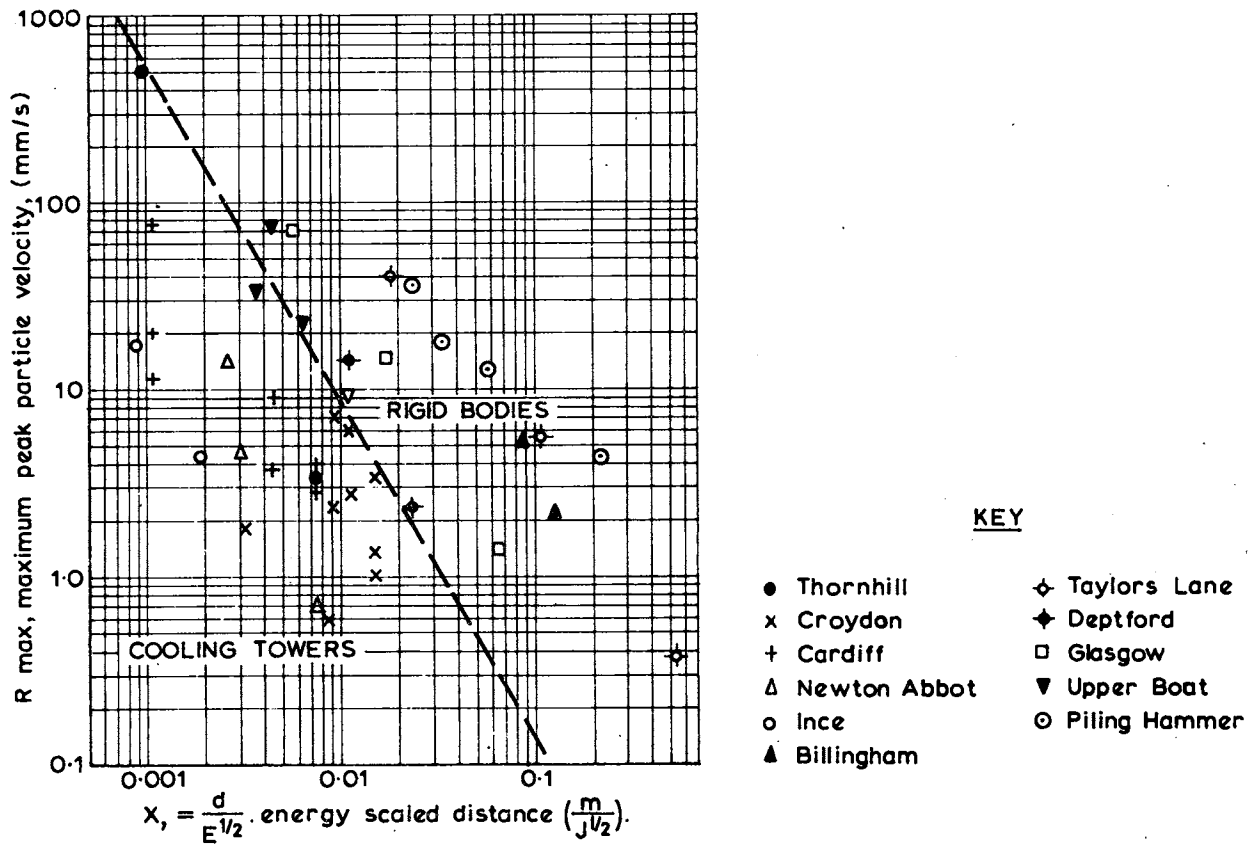


Fig.8. Scaled distance relationship - impact

consideration of the different wave types is rarely justified and the scaling laws described above do not generally take these factors into account.

THE INSTRUMENTATION CHAIN

43) Modern instrumentation systems consist of sensing transducer, signal conditioning, signal recording and/or storage, signal analysis and signal display.

44) The sensor, as has been pointed out, almost invariably is based upon a mass-spring element (Willmore 1961, Ref. 17) (Willmore 1977, Ref. 18).

45) In older systems (notably the Cambridge Vibrograph) the chain was entirely mechanical with the signal being proportional to displacement and displayed as an impression on a clear strip. (Harris and Crede Ref. 8). This unit is no longer manufactured. Simple mechanical oscillographs are now represented by the Ampligraph and Combigraph (Table II).

46) A mass-spring element may be so arranged as in a geophone to give an electrical output linearly proportional to particle velocity. This is done by setting the natural frequency below the expected ground frequencies. Such devices are widely available with a natural frequency ranging from 0.5 Hz to 75 Hz. Devices with natural frequency of about 5 Hz are widely favoured (Buckley & Smith, 1977 Ref. 19). The amplitude response characteristic of such a transducer is shown in Fig. 9. The moving coil device is capable of being used in other ways and in conjunction with galvanometers and appropriate damping and amplification may be developed into a broadband unit. (Willmore, Ref.17). For most engineering purposes a geophone with critical damping feeds into a galvanometer of high natural frequency or on to a tape recorder. (Kuehn 1977, Ref. 20, Miles 1977, Ref. 21). In this mode useful range of frequency is limited to 5 - 200. For special studies a geophone can be overdamped at the penalty of some non linearity in amplitude and phase. It may be noted that a moving coil device operating below at natural frequency gives an output (much diminished) linearly proportional to acceleration.

47) Most geophones have a limit set by the maximum excursion of the coil relative to the case. This may be only a few millimetres. For this reason 'nominal envelopes' (Fig. 10) plotted from manufacturer's quoted ranges of measurable velocity and frequency are inadequate. An advantage of the piezoaccelerometer is that this limitation does not arise.

48) Piezoelectric accelerometers consist of a crystal which responds to load by generating an electric charge across its faces, attached to a mass (Pretlove 1966, Ref. 22). The system has a very high natural frequency and the force applied to the crystal is proportional to the acceleration of the mass. Piezoelectric type transducers are usually used with impedance mat-

ching pre-amplifiers, usually charge amplifiers.

49) One type has a built-in amplifier giving voltage output and is capable of operating to very low frequencies (B & K 8306). When operating over great cable lengths electrical noise may become a problem. This is minimised by using low noise cables. Piezoelectric devices, as distinct from geophones require a d.c. voltage. When cables are long this can be provided by batteries at the sensor itself.

50) Although other transducers are available (Pretlove *ibid*) in the U.K. geophones and piezo-accelerometers are almost exclusively used in general purpose ground vibration measurements although reluctance accelerometers are available.

51) Buckley and Smith Ref. 19 have discussed the assembly of a triaxial pack of accelerometers and has mentioned cross sensitivity and described how transducer performance figures are quoted, drawing attention to the importance of the mounting. We will return later to the whole question of sensor/ground coupling.

52) The simplest way of presenting an electrical output is to use a meter, either with an analogue (pointer) or digital display. Such a display is appropriate for a peak level measurement from a periodic continuous harmonic source or an RMS level such as may be given as an index of human tolerance level. With suitable circuitry either fixed narrow band or third octave frequency analysis can be undertaken (Ashley 1977, Ref. 23). Such instruments would normally use a single axis transducer. It is however possible in principle to combine in amplitude and phase the output of a triaxial pack to give a single peak vector signal, but digital methods would probably be required. General purpose vibration meters are of this type and Miles 1977, Ref. 21 warns that the time constants involved may lead to gross errors in measuring impulsive events.

53) The use of a simple peak level detector with a sufficiently broad band non distorting sensor (1-200 Hz) can be effective with complex periodic and quasi-stationary random vibration.

54) O'Neill 1977, Ref. 24 has drawn attention to the difference between systems designed to capture all the data and monitoring devices which may be continuously activated or passive and awaiting a triggering. These latter units are represented by the strong motion recorders in Engineering Seismology (Halverson 1971, Ref. 25). Several such systems have been reported (Skipp, Tayton 1971, Ref. 26). In recent years the development of solid state modules permits storage of data with high rate of sampling, sufficient to define complex motion and with the facility to recall in a visual or tape format either on command or if a preset signal level has been achieved. Examples are given by Stenling 1977, Ref. 27.

55) For rapid survey and diagnostics a simple combination of transducers and portable CRO has

TABLE II. COMMERCIALLY AVAILABLE VIBRATION MEASURING SYSTEMS SPECIFICALLY COVERING BLASTING

Manufacturer	Nitro Consult	Nitro Consult	Nitro Consult	Nitro Consult	Sprengnether	Sprengnether
Model	Ampligraph	Combigraph	Vibracorder	Vibrascope	VS-1100	VS-1200
Sensor	Mass on spring	Mass on spring	Geophone	Geophone	Geophone	Geophone
Measured parameter	Displacement	Displacement	Particle velocity	Particle velocity	Particle velocity	Particle velocity*
Parameter range	5×10^{-3} to 2 mm	5×10^{-3} to 2 mm	Up to 100 mm/s	20 mm/s max. or 200 mm/s max.	0.05 to 180 mm/s	As VS-1100
Frequency range, Hz	3 to ?	3 to ?	5 to 500	5 - 200	1.8 to 250	As VS-1100
Number of channels	1	1	4	3	3	4
Recording method	Pressure stylus on wax paper disc	As Ampligraph	Pressure-sensitive paper chart	Digital read-out or chart recorder	Direct-write dry photographic paper	As VS-1100
Chart speeds, mm/s	0.003	0.003, 20, 40, 60	?	-	100	As VS-1100
Sensor details	In record unit; wall or floor mounting	As Ampligraph	Free individual sensors	1 component or resultant of 3 components	Free triaxial unit	As VS-1100
Special features	-	Long or short term recording	Peak level detector	-	Sensor matched to soil density	Extra amplifier ranges
Recording duration	8 days	8 days or blast duration	28 days	1 month between battery charges	Blast duration	As VS-1100
Power	Clockwork	Clockwork or mains	Mains; battery standby	2 x 9V standard batteries or 4 x 1.5V torch batteries	Rechargeable battery	As VS-1100
Weight, kg	9	8	35	14	24	As VS-1100
Size, mm	285 x 175 x 70	As Ampligraph	440 x 265 x 300	-	177 x 177 x 177	As VS-1100
Weather protection	Yes	Yes	No	Yes	Yes?	As VS-1100

*Displacement or acceleration option

Kinematics	Sinco	Environmental Equipments	Atlas Copco	Vibration Measurement Engineers	Vibration Measurement Engineers	Vibra-Tech Engineers
VM-1	S-2	Vibrocorder	Vibrapet	Model F	Seistector models 1400 and 1400 MP	Vibra-tape GMS.4
Optional	Geophone	Geophone	Geophone	Geophone	Geophone	Geophone
Particle acceleration	Particle velocity	Particle velocity	Particle velocity	Particle velocity	Particle velocity	Particle velocity
$10^{-6}g$ to $1g$	1 to 450 mm/s	0.2 to 200 mm/s	0.02 to 550 mm/s	0.1 to 100 mm/s	25 mm/s max. or 50 mm/s max.	100 mm/s max.
0.1 to 25	6 to 150	6 to 50	5 to 400	5 to 200	5 - 200	1 - 200 (min.) (special amplifier) 5 - 500 (min.) (air pressure)
1 or 2	6	1 or 2	6	3	4	4 (3 seismic, 1 air pressure)
Heated stylus on wax paper chart	Direct-write dry photographic paper	Spark stylus on paper chart	Direct-write dry photographic paper	70 mm film	Pressure-sensitive paper chart	Magnetic tape cassette + meter
25, 50	25, 127, 250, 1270	1, 2, 5, 25, 50	100, 250, 500, 1000	100	25 mm/h	1 - 7/8 in/s
In record unit; with level	2 sets of free triaxial units	Free sensor on inertia block	Free sensors on mounting block	Free triaxial unit, with level	Triaxial unit on recorder	Free triaxial unit
Filter modules optional	Long cables optional	Acceleration sensor option (piezo crystal)	Low frequency geophone option	Sound channel option	Model 1400 with resultant peak motion recorder	Sound channel option
Blast duration	Blast duration	Blast duration	Blast duration	Blast duration	24 hour basis	Blast duration
Rechargeable battery	Rechargeable battery	Rechargeable battery	Rechargeable battery	Rechargeable battery	Mains with 8 hour standby power path	Standard battery (Ever Ready 1209)
11	20	15	64	16	4.5	11
203 x 304 x 266	220 x 500 x 400	310 x 300 x 110	580 x 300 x 300	228 x 247 x 492	121 x 279 x 140	-
Yes?	No?	No?	Yes	Yes?	Yes	Yes

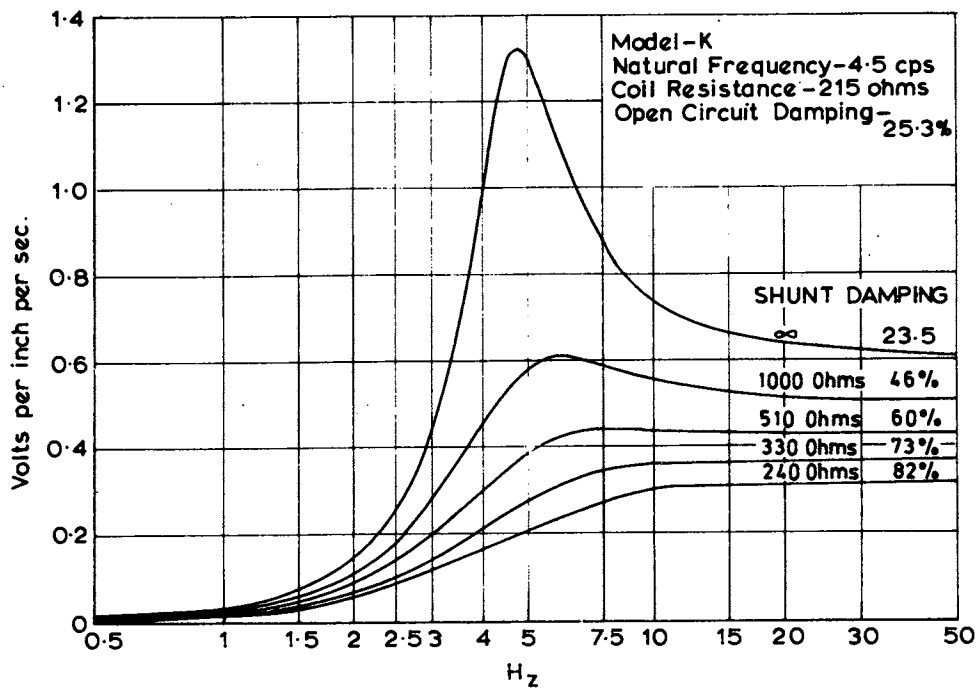


Fig.9. Amplitude response characteristic - commercial geophone

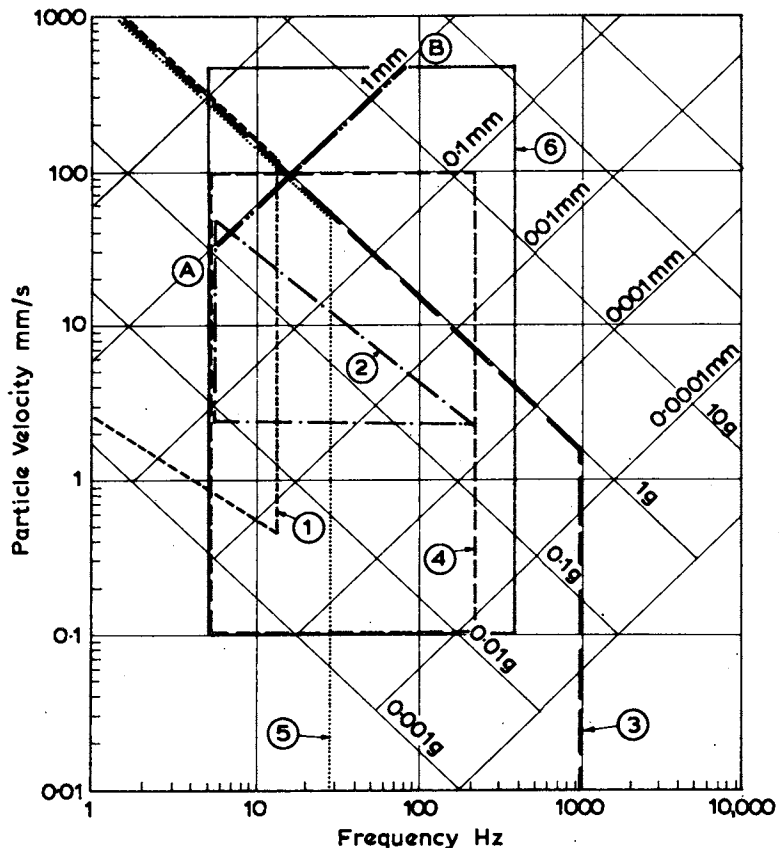


Fig.10. Useful operating ranges of some vibration measuring units: (1) Cambridge Vibrograph; (2) U.S.B.M. recommendation (USBM RI.6487); (3) B&K 8306 low g accelerometer; (4) V.M.E. - nominal; (5) V.M.l.; (6) Vibrapet; (A-B) probable limits on geophone coil-case excursion - estimated

much to commend it. Many combinations using such commercially available units as transient analysers are conceivable although there is now an increasing tendency to use FM tape recorders with a U.V. recorder giving 'on site' assurance that all data has been captured and also the facility for off site analysis.

56) Instruments have been specially designed to be used to measure ground vibrations set up by blasting. An early specification suggested by the United States Bureau of Mines is illustrated in Fig. 10, and was the basis of at least one commercial device. Several commercial units are available and are listed on Table II. They are all compromises. Some are limited in the low frequency response others by using pen recorders are limited in high frequency response.

57) Units with geophone type sensors include V.M.E. Sprengnether, Sinco Vibratape. Others use accelerometers (Vibracorder). There is a variety of recording methods; pen on heat sensitive paper (Vibracorder), dry photographic paper (Vibrapet), photographic film (VME), magnetic tape (Vibratape). The Kinometrics VMI has provision for alternative sensors and they also can provide a force-balance accelerometer of DC-26 Hz with dynamic range ~ 80 dB.

58) A special feature of much U.S. equipment is the provision to obtain tamper-proof data for legal purposes.

59) Some units have sensing heads with orthogonally mounted sensors giving the option a combined output being either resultant peak computed either vector or the root of the sum of the squares of the peak component in each direction. None give a truly phase corrected resultant. The development of one such unit is described by Diem 1972, Ref. 28.

60) The list in Table II is by no means complete and the literature abounds in incomplete descriptions of measuring devices.

61) Most blast vibration recorders (like strong motion seismographs) are essentially single point systems although two (Vibrapet and Sinco) have six separately usable channels. The sensors are often too heavy to be located on light responding elements. In recent years however there is usually a provision for the components plus one channel for air blast over pressure. The best modern units are designed to measure peak particle velocity in three senses at the foundation of buildings subject to typical blasting vibration.

GROUND COUPLING

62) The positions of measurement have been mentioned (Splittgerber 1977, Ref. 29) and Buckley and Smith 1977, Ref. 19 has drawn attention to the importance of avoiding spurious signal levels. The effect of ground coupling variations on the response of an accelerometer situated directly on the surface of the ground

and on a large aluminium plate on the surface of the ground is seen in Fig. 11 and 12 in both time and frequency domains. Such response problems are well known in exploration geophysics (Bycroft 1957, Ref. 30) and have recently been the subject of renewed study (Boztas 1976, Ref. 31). For minimum distortion the mass ratio should be low. Mass ratio for vertical response is mass divided by the product of soil mass density and the cube of the effective radius of contact (Fig. 13).

63) For a typical geophone or accelerometer resting on the surface of a dry loose soil a magnification of 2.7 is possible at frequencies of 90 - 100 Hz. By using the theory of the elastic half space and suitable analogs it can be shown that when a typical sensor is connected to a moderately stiff rock such magnification would not arise at frequencies less than 3000 Hz. It has also been shown that by burying a sensor about 200 mm in the loose soil and tamping sand back around it, adequate coupling without undue distortion is obtained.

THE USE OF MEASUREMENTS

64) Measurement of ground vibration may be required in order to enforce a standard, to diagnose a problem or provide data for design. In considering the first purpose we must refer to codes, standards, court judgements etc., and the basis on which such standards have been constructed. O'Neill 1977, Ref. 24 describes the legal aspects. Empirical relationships between damage to structures and peak particle velocity have in the main been derived from instrumentation limited in its frequency response to the range 10 - 100 Hz, which is within the range that the critical frequency of many conventional low rise buildings fall. There are however structures with lower natural frequencies and it is known that ground vibrations from a number of sources may have significant peak signal magnitudes below 10 Hz (Skipp et al 1972, Ref. 7). There has also been a wide disparity between the levels of the single parameter criteria, "particle" velocity associated with "onset of damage".

65) Threshold levels associated with architectural damage have been suggested ranging from 5 mm/s to 50 mm/s (See Table III) and Fig. 14. This particular kind of damage (minor cracks, extension of old cracks less than say 0.02 mm wide) is regarded by an engineer as of little consequence but the population at large cannot differentiate between significant and insignificant damage. The vibrations at these levels would be regarded as intrusive and in the worst case as degrading the serviceability of the dwelling. (ISO DP.4866)

66) Within the 5 - 50 mm/s band various countries have established code thresholds, 10 mm/s in Czechoslovakia, 20 mm/s in Australia (AS.23, 1967). In countries without formal codes good practice usually takes into account the intrusive element without specifying a particular damage state. In the U.K.

TABLE III
SOME GUIDES TO 'ACCEPTABLE' VIBRATIONS FOR
STRUCTURES - IMPULSIVE LOADING

LIMITING VALUES OF PARTICLE VELOCITY, BLASTING
 VIBRATION FROM VARIOUS AUTHORITIES.

DAMAGE	PROPAGATION VELOCITY		
	1000-1500	1000-3000	4500-6000
No noticeable cracking	18	35	70
Fine cracks in plaster	30	55	100
Deep cracks	40	80	150
Serious cracks	60	115	225

After Gustaffsson

Class of structure	V_R max mm/s
I Ruins, damaged historic buildings	2
II Buildings with visible damage, cracks in brickwork	5
III Buildings without damage in structurally good condition with plaster cracks	10
IV Well stiffened industrial buildings	30 - 40

After Baule/DIN 4150 (old version)

Damage state	Particle Velocity mm/s
Serious cracking	228
Cracking	152
Fine cracks and falls of plaster	110
Caution	76
No noticeable damage	76

After Langfors

Damage state	Particle Velocity maximum component - + mm/s
Major damage (Fall of plaster, serious cracking)	165
Cracking	110
Caution	51
Safe	51

After USBM

Category of damage	Range V_R in - mm/s ⁺⁺ Onset of damage
Threshold (Non load bearing elements)	3 - 5
Minor damage	5 - 30
Major damage	100

After ISO/TC/108/SC.2N16.DP4866 Proposals

Notes:

- + - measured in ground near structure
- ++ - measured on structure foundation

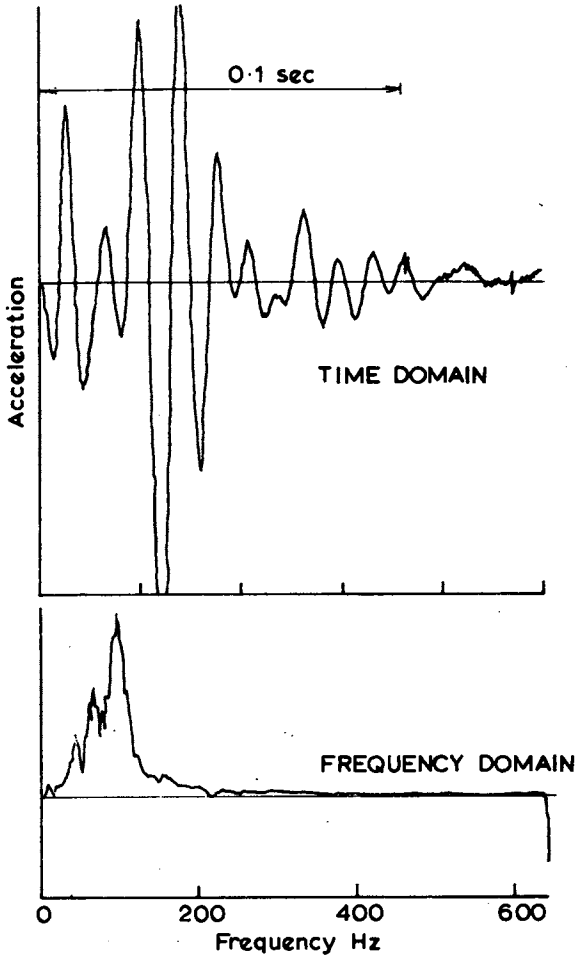


Fig.11. Response in time and frequency domains of an accelerometer on ground surface - mass ratio = 22.5

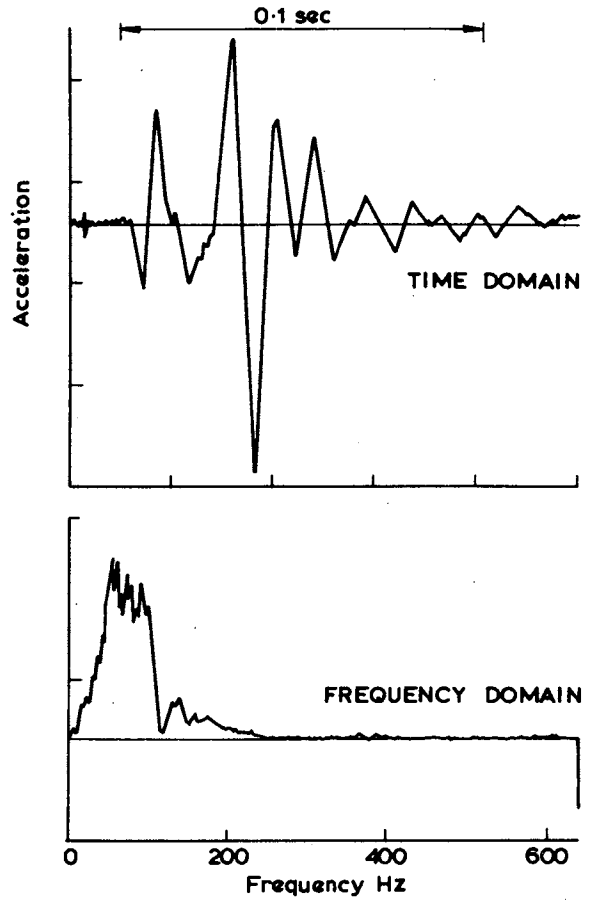


Fig.12. Response in time and frequency domains of an accelerometer on ground surface - mass ratio = 1.9

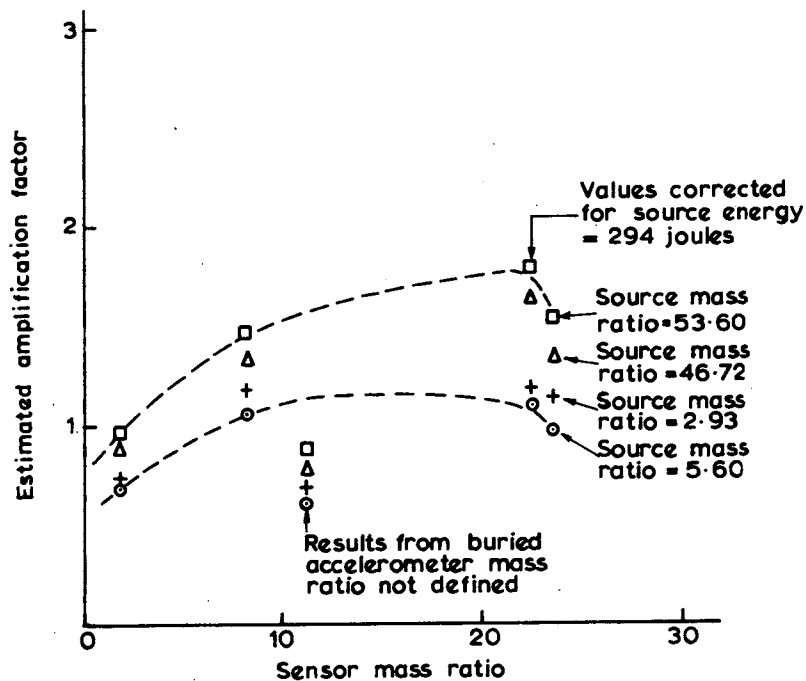


Fig.13. Apparent magnification of peak response versus mass ratio (vertical acceleration)

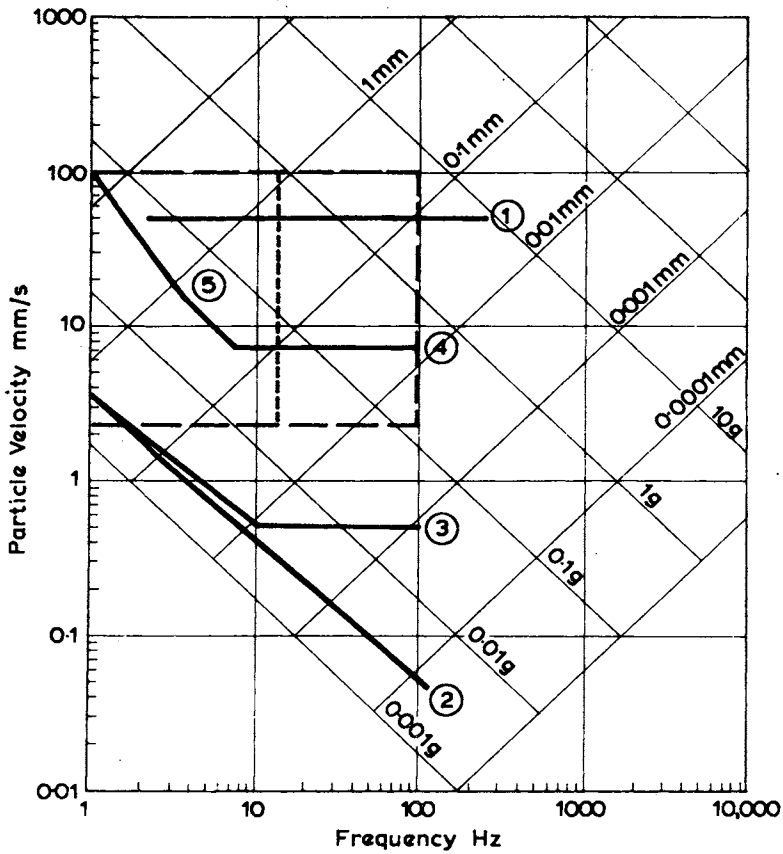


Fig.14. A selection of criteria for vibration limits: (1) threshold, U.S.B.M. - buildings; (2) threshold, human whole body perception, McKay (see Ashley, 1977); (3) threshold, human whole body perception (see Staffens, 1966); (4) I.S.O. 2631 - 1974, 8 hour fatigue decreased proficiency; (5) threshold, buildings ISO DP.4866, 1976

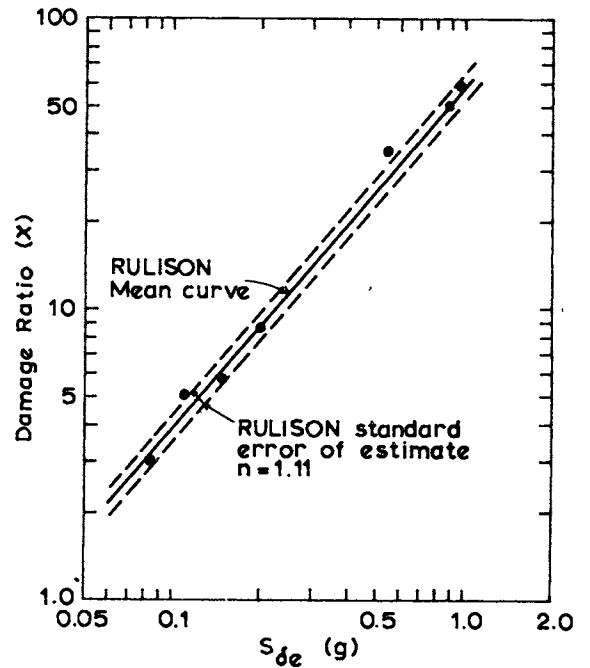


Fig.15. Damage ratio and spectral acceleration (after Scholl)

for example for tunnel blasting, 10 mm/s has been the aim in densely populated areas and 25 mm/s in sparsely populated areas (Ball and Watt, 1976 Ref. 32).

67) Often the properties of the foundation materials are taken into account (Gustaffsson 1971 Ref. 33) giving a lower threshold of 18 mm/s on soft soils.

68) The most substantial data base has undoubtedly been that established by the United States Bureau of Mines and recent studies on conventional North American wooden frame and gypsum plaster board houses have pointed to the importance of air blast and confirmed the USBM criteria (Wiss 1974, Ref 35, Siskind 1975, Ref. 36). There are however reports of minor damage to European brick and masonry structures at levels between 7 - 40 mm/s (Dvorak 1962, Ref. 37 and Drozd 1972 Ref. 38) but the instrumental methodology has been questioned (Nicholl 1972 Ref. 34).

69) It must also be appreciated that ground vibrations from impact or blasting may have to be limited because of the effects on sensitive instruments or important protective systems (Steffans 1970, Ref. 39/Skipp & Tayton, 1971 Ref. 26, BS.142 1966, Ref. 40).

70) For a structure with important natural frequencies near those carrying significant amounts of energy in the ground vibration, peak particle velocity has theoretical attractions as a single parameter index of the structural response in terms, ultimately, of induced dynamic stresses. We would not expect this convenient relationship to hold for all buildings and all ground motions.

71) Much less controversy attends the criteria for continued vibration of buildings although little further detailed experimental work has been published since the classical work of Koch 1953, Ref. 41 (see also Steffans 1966, Ref. 42). Gasch 1974, Refs. 43, 44 relates peak particle velocity to fibre stress in beams as follows:

$$\hat{\sigma}_{max} \approx \sqrt{E_d \rho} \cdot 3.6 g_{eq} / G_b \cdot k_n \cdot \hat{u}_{max}$$

where

E_{dyn} = dynamic elastic modulus of beam material

ρ = density of beam material

G_{eq} = self weight loading plus live loading

k_n = a mode factor (between 1 or 1.3)

\hat{u}_{max} = maximum particle velocity at mid span of beam (or floor)

$\hat{\sigma}_{max}$ = extreme fibres stress

Recently Gasch has extended the concept to response to random vibration.

72) Traffic vibration levels and the long term effects on buildings have been reviewed by Bata 1971, Ref. 46 and expressed as average acceleration. For example the category "probable origin of cracks in recent decades" for buildings near a main road carrying more than two vehicles a day would be between 50 mm/s/s. At 10 Hz and a sine impact, this gives a value less than 2.0 mm/s.

73) The threshold of vibration affects on dry and saturated sands have received recent attention but have not been incorporated into codes (Richart et al 1970, Ref. 16).

74) Where we are concerned not with establishing a single parameter index of damage or discomfort but with describing a ground vibration sufficient to estimate its effect on some structure it is necessary to have in mind the way in which that response would be calculated. Splittgerber, Ref. 29 makes use of a transfer factor between peak velocity amplitudes measured at ground floor and at various parts of buildings. In order to evaluate a more complete picture of the structural response it is necessary to use not just a peak or RMS velocity but the time history of the ground motion, or its description in the frequency domain (Medearis 1975, Ref. 45). We are then entering upon the field proper of earthquake engineering.

75) In order to estimate the peak response of say a simple structure or component (a relay cabinet for example) fixed to the ground it is convenient to describe the ground motion in terms of a response spectrum (Fig. 3) which is the peak response to the ground motion of a series of one degree of freedom mass springs of given damping. For example a relay cabinet of natural frequency 4 Hz mounted on the ground and having zero damping would have a peak horizontal velocity in its fundamental frequency of 1.5 times ground velocity when subjected to a ground motion having the response spectrum of Fig. 3. (In fact relay cabinets commonly have fundamental natural frequency around 10 - 15 Hz as a shear beam). Magnification factors between ground and relay panels can range from 5 - 20.

76) The value to be assigned to a damping term in estimating the response of buildings is of concern to earthquake engineers. For most man made ground vibration problems the response system is elastic and low damping ratios are appropriate (2% - 5%). Similarly while source processes may be plastic, transmission is usually at small strains and elastic theory is applicable. This condition would not apply to very near field situations (large explosions, impact etc.) when ground particle velocities exceed many hundreds of mm/s, but holds for most practical problems.

77) Recently the limitations of a simple single parameter index of structural damage thresholds for short duration (1 - 10) ground vibrations

have been recognised. The statistical nature of the problem has also been pointed out. (Blume 1969 Ref. 47). A 'damage ratio' has been defined as the percentage of buildings exposed to the same vibration history for which there is reported damage. (Schol 1974 Ref. 48). When applied to low rise buildings subjected to the ground vibrations from an underground nuclear explosion (Rulison) it would appear that a damage ratio of about 5% was associated with a peak spectral acceleration of 0.1 g. (See Fig. 15). The peak spectral acceleration refers to a maximum in a response spectrum. It is usually several times greater than the maximum ground surface acceleration. (Schnabel & Seed 1973, Ref. 49). An important factor is the duration of ground shaking and for blast vibrations the effect of this factor has not been systematically studied.

78) Elementary considerations of the response of structures would lead to the selection of a criterion based upon the differential displacements in a building giving rise to differential stresses, taken in conjunction with a 'fatigue' factor and some knowledge of initial stress state. This calls for information on the relationship between ground vibration, building response, building element response and monitoring of the consequences, usually in terms of crack intensity (Fang 1977, Ref. 50). Crack monitoring has been undertaken (Grover 1971, Ref. 51). It has been shown that very low levels of vibration accelerate the rate of crack formation (Wall 1967, Ref. 52) but probably only up to a limit which would be achieved in time anyway with new construction.

79) Because there are as yet no generally agreed levels of single parameter indices of damage there has been no accepted standard of instrument performance and use. This has in turn affected the credibility of empirical 'relationships' and restricted the application of currently available methods of estimating the proper response of structures. There are no agreed standards for the construction and use of vibration measuring instruments in ground engineering but currently before ISO TC.108/SC2 Ref. 53 is a proposal on instrumentation for the measurement of vibration affecting structures. This proposal envisages three categories of instrumentation. The first category would have a useful frequency range of from 1 - 1000 Hz and would cover the proper characteristics of most kinds of ground motion with a view to calculating the response of structures. The second category would have a useful operation frequency range of 5 - 100 Hz and would cover the most common range of frequencies in ground vibration and the natural frequencies of most buildings. A third category calls for only peak level measurement without a full time history being recorded.

80) A vibration measuring system conforming to the requirements of ISO 2631, Ref. 54 somewhat different in that RMS acceleration levels are called for (Ashley 1977 Ref. 20) and there is the possibility of using some equivalent to

the 'exposure' concept in energy terms as adopted in noise codes and standards.

CONCLUSIONS

81) The man made ground vibrations of concern to the engineer range from the simplest continuous periodic motions to complex non stationary random motions and transients.

82) The technical capability now exists to satisfy all the requirements of ground vibration measurements but in the absence of a clear guidelines a diversity of equipment has developed not all of which is adequate or properly used. Data collection, processing and analysis in terms of structural response is now available to those who need it.

83) In most cases however the measurements are made in order to control or restrict some obtrusive vibration. There is then a demand for simple index parameters of human discomfort and structural damage. Progress in the former field has been substantial in recent years but the same cannot be stated of the latter. Indeed there are indications that with impulsive and short duration vibrations advances will not be made until they are properly described in their frequency domains. Damage occurrences should be treated statistically having regard to the response characteristics of different kinds of structures. In the meantime the use of threshold values of peak particle velocity will no doubt continue so it is important not to devise elaborate codes on a narrow data base. Where a low threshold has been set the essentially probabilistic basis and wide "safety margins" must be realised so that for particular cases society does not impose onerous constraints which may not be economically justified.

84) For more sophisticated studies where ground, structural, or even component and equipment response is needed, appropriate instrument systems can be assembled from currently available units.

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3. Assessment of seismic hazard in the UK

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Historical files of earthquakes are the major data source for seismic hazard assessment in the UK. Extreme value statistics may be applied to these data sets and recurrence intervals obtained for different energy levels. On the basis of simplified recurrence statistics 'comparable' strong-motion data may be selected as representative of a regional seismic hazard.

INTRODUCTION

1. The constructional engineer is expected to assess the effects of all phenomena which might affect his designs. Before building codes may be established to protect structures against damage caused by earthquakes, it is essential to develop an acceptable macrozoning technique. Inter-disciplinary discussion must be a vital part of an overall hazard assessment, but it is also necessary for the seismologist to establish the point at which his analysis of seismic hazard finishes and the earthquake engineer begins his design analysis.

2. Earthquake epicentres may be represented cartographically to give a qualitative impression of the spatial distribution of seismicity. However, such maps are probably not time invariant. Nor is it acceptable to pick one earthquake and assume it will reveal all aspects of a regional seismic hazard. A statistical analysis is essential; although the degree of sophistication will probably vary with the economics of the problem in hand. For the constructional engineer to design earthquake-proof structures he ideally needs to know several facts which include:

- i) The spatial distribution of earthquake epicentres within its tectonic setting.
- ii) An estimate of the energy released at the earthquake focus or a parameter which is related to the damage potential of an earthquake; for example, magnitude, seismic moment, intensity and radiation pattern.
- iii) How this energy attenuates with distance.
- iv) The statistical frequency of occurrence of seismic energy release which is expected at different energy levels.
- v) The dynamics of ground vibration caused by the propagation of seismic energy.

3. This paper describes the application of some hazard assessment techniques to the UK, but because of the inadequacies of the data available no pretence is claimed at achieving an ideal and exact hazard assessment which may be ubiquitously applied at each point within the UK.

TECTONIC AND GEOLOGICAL SETTING

4. North West Europe is contained within the Eurasian plate in a mid-plate position and so the major earthquakes associated with plate boundaries are not experienced (Fig. 1). The lithospheric properties of the upper mantle and crust will be characterised by an oceanic to continental transition. Found within the context of this overall trend in the structure are three major orogenies which relate to the major structural divisions of the British Isles. The three orogenies which have formed the major faults and folds are the Caledonian, Hercynian and Alpine. Whenever tectonic faulting and folding occur earthquakes are likely to be in evidence.

5. The Caledonian orogeny is of great significance and the folded regions extend from northern Norway to western Ireland. The uplands which now exist in the British Isles in the mountainous areas of Scotland, Wales, north west England and north west and south east Ireland were predominantly affected by this orogeny. The clearest tectonic features occur in Scotland where four major fault trends can be observed. The Midland Valley of Scotland is a graben feature contained by the Southern Upland Fault and the Highland Border Fault. In the north west is the Moine thrust which runs from Skye to the coast in north Sutherland; further to the north west of this thrust zone lies the ancient Pre-Cambrian region. The most striking tectonic feature with a global significance is the Great Glen fault dividing the North West Highlands from the Central Highlands.

6. The Great Glen is a strike slip fault which according to Holmes has a left lateral horizontal displacement of about 65 miles (ref. 1). This strike slip fault is a line of crustal weakness and although most of the displacement was probably during the transition from Devonian to Carboniferous times about 350 million years ago, there is a clear correlation between the line of the Great Glen and local earthquake epicentres. This is the clearest correlation

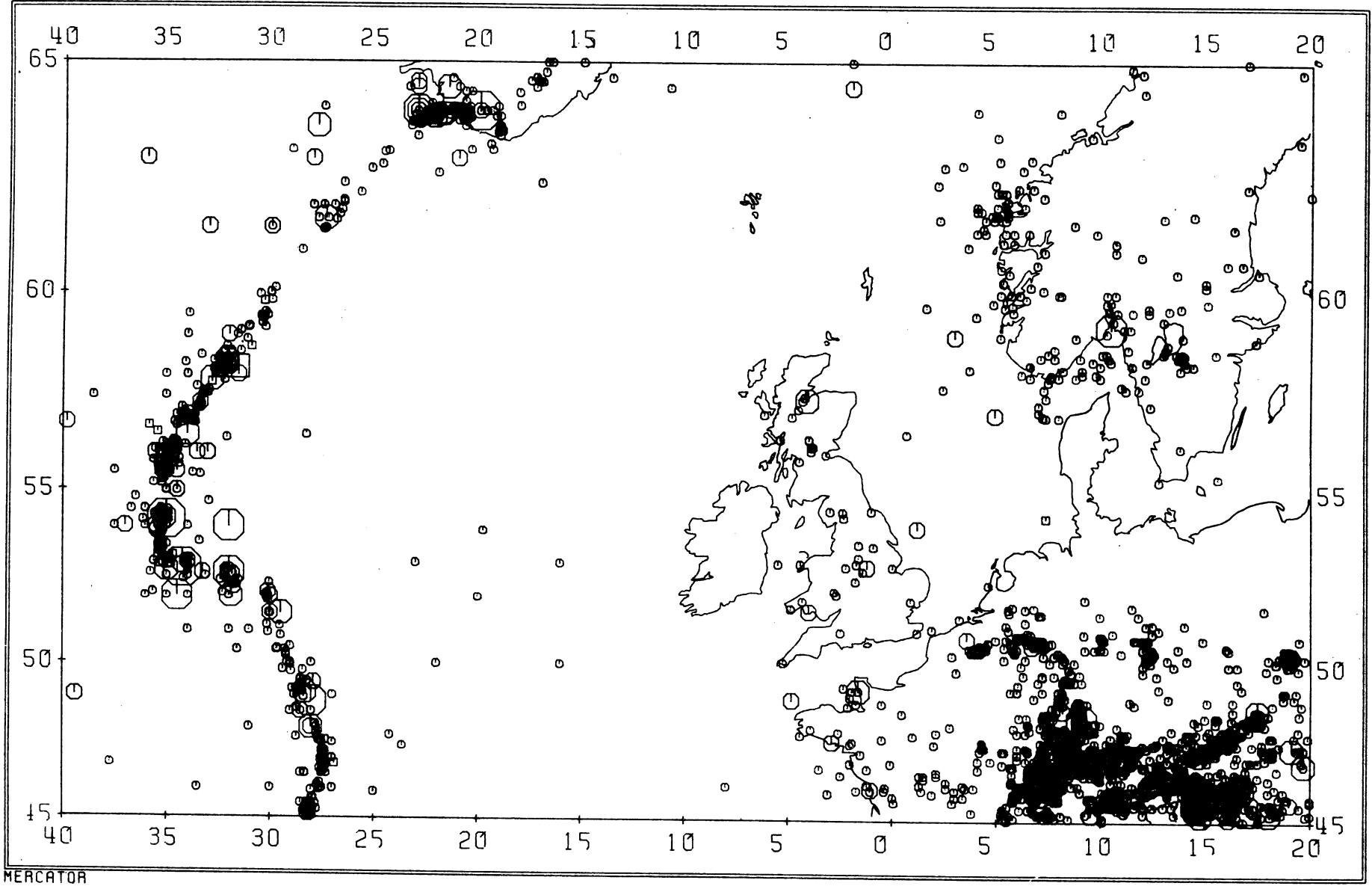


Fig.1. Seismicity from the Mid-Atlantic Ridge to Western Europe: surface wave magnitudes are plotted at each epicentre

which may be made between the tectonics and earthquake activity of the UK with the data presently available.

HISTORICAL DATA

7. Any assessment of seismic hazard requires knowledge of the spatial and temporal distribution of earthquake sources: for areas of low seismic activity like the UK this information is relatively difficult to obtain. Instrumental seismology got under way at the turn of the century but most of the instruments available recorded at low gains. Because of this lack of instrumental data, resort is made to macroseismic data solicited from the public by contemporary survey or a later research into public archives. In 1884 the Irish seismologist O'Reilly produced (ref. 2) his own map representing UK seismic activity (Fig. 2). In this map different symbol sizes represent the number of tremor reports at a particular location; this is representative of the seismicity. The Montessus de Ballore (ref. 3) in 1896 produced a map (Fig 3) which shows the spatial distribution of reported shocks independent of their intensity. He went further and produced a rudimentary seismic risk map (Fig. 4) which effectively represents the annual number of reported shocks per unit area. Ballore's map is instructive. It reveals regional differences in activity; it shows the influence of swarm phenomena at Comrie and Menstrie on the overall picture; but it lacks any information about the relative size of the earthquakes. The data base for these two studies must necessarily be quite similar although the final representations differ in style. The historical data file becomes a little more homogeneous in 1924 when Davison (ref. 4) sifted through the available earthquake catalogues and published his own work on British earthquakes. The major contributors since Davison's time are Dollar (ref. 5) and Tillotson (ref. 6).

8. Much of the data extracted from these sources still remains macroseismic in nature. For each reported earthquake it is possible to assign a maximum felt Intensity. Lilwall (ref. 7) contoured the distribution of maximum felt intensities for the UK and produced the map of Fig. 5, the various Intensity scales used for describing British earthquakes are here rendered onto the Modified Mercalli Scale. Immediately clear is the tectonic feature of the Great Glen although the dumb-bell shape will be slightly smoothed by the relocation of one of the larger earthquakes following recent work by Browitt and Burton (ref. 8). Davison's 1888 "Inverness" earthquake was, in fact, centred nearer the middle of the Great Glen in the region of Invergarry.

9. One item of macroseismic data which may be further exploited is the felt area of an earthquake. If both depth and felt area are known then an estimate of earthquake size or magnitude may be made. Lilwall suggests the relationship

$$m_b = 0.8 + 0.32I + 0.61 \log_e D \quad (1)$$

$$\text{with } D^2 = h^2 + r^2 + k^2 \quad (2)$$

where m_b is the body wave magnitude, I the Modified Mercalli Intensity, h the depth (km), r the epicentral distance (km) and k an empirical adjustment which allows for the finite focal volume which matters at short ranges. Esteva (ref. 9) suggests $k = 20$. Equation (1) may be recast in terms of the known felt area A sq km within isoseismal 3 as

$$m_b = 1.4 + 0.7 \log_{10} (A + 1256) \quad (3)$$

Applying this technique to the known felt areas and the maximum intensities and plotting the resulting estimates of m_b gives us Fig. 6. This link between macroseismic data and an instrumental magnitude estimate still requires more detailed study to obtain a better known precision on conversion.

10. Fig. 6 shows the lineation of the Great Glen, the swarm activity centering on Comrie and Menstrie and an earthquake population stretching from South Wales into the Midlands. There are large areas with low levels of seismic activity, but because the data is largely macroseismic it may be that this is only a correlation with low levels of population. This could be true for central Wales and the eastern Highlands of Scotland. In eastern England the picture of low activity is fundamentally modified by the Colchester earthquake of 1884, which stimulated a high intensity for the UK. This picture may be modified further if more information is obtained about the apparently large London earthquake of 1580.

11. Fig. 7 shows the distribution of earthquakes which have an m_b magnitude estimated to be greater than 4. These larger events are the major contributor to the observed distribution of maximum intensity (Fig. 5) and about one such event is expected each year. The seismicity of the Great Glen still remains clear but it is now also possible to detect a lineation from South Wales out to the Dogger Bank earthquake of 1931, passing through some of the larger Midlands earthquakes. Several of these earthquakes have an estimated depth (many of the shallow earthquakes are 'fixed' at 5 km depth) beyond 5 km. It is likely that these earthquakes correlate with the deep crustal transition between the Caledonian regions to the north west and the London platform to the south east.

RISK STATISTICS AND ATTENUATION

12. Given a sufficiently lengthy historical data set, it is possible to assign return period estimates for different earthquake parameters: for example, magnitude, or ground motion parameters described by intensity or acceleration values.

13. For a general statistical analysis of earthquake activity in a region it is necessary to assume that the earthquakes are mutually independent events: this necessarily precludes aftershock sequences from a general analysis. It

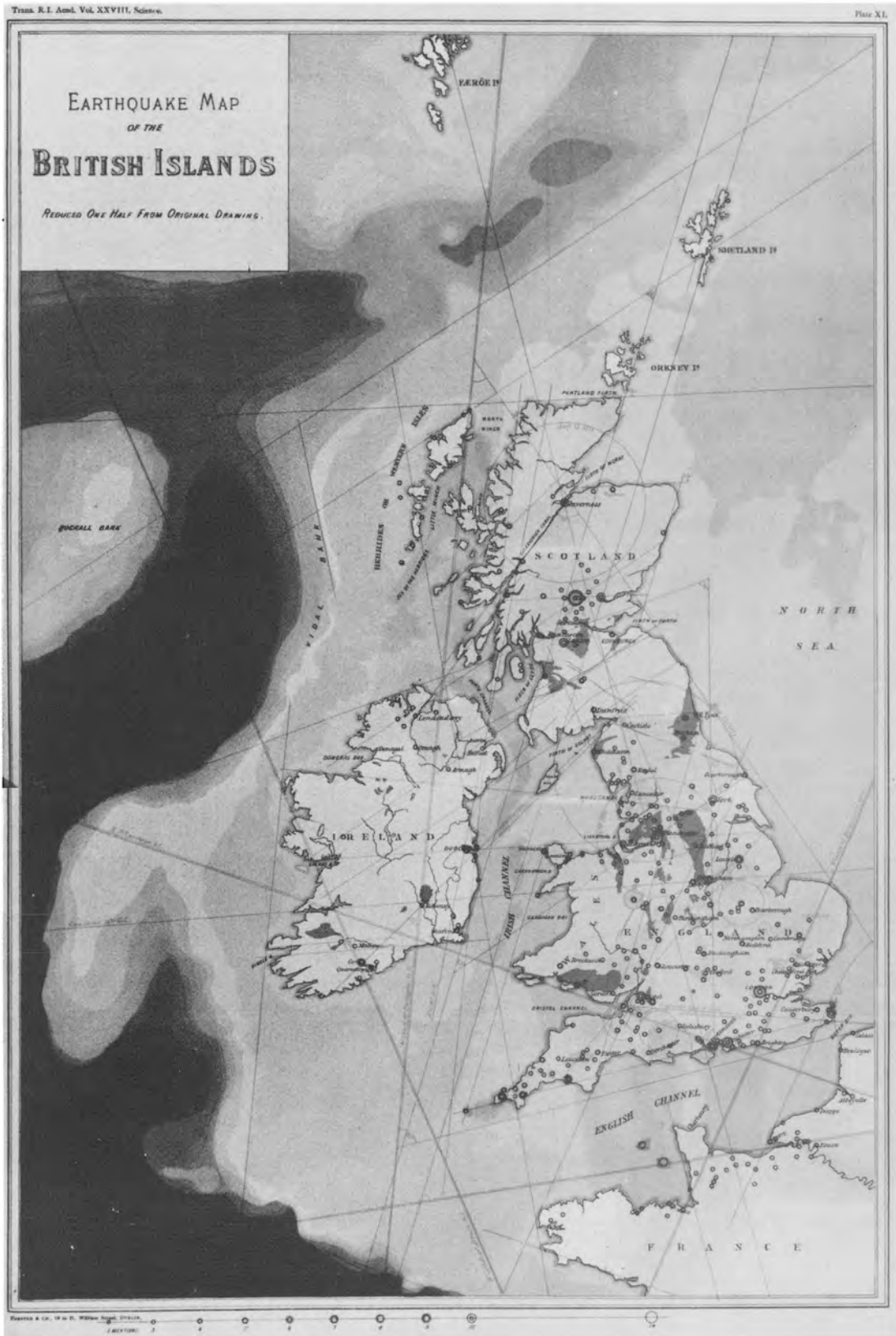


Fig.2. O'Reilly's seismicity map presented in 1884

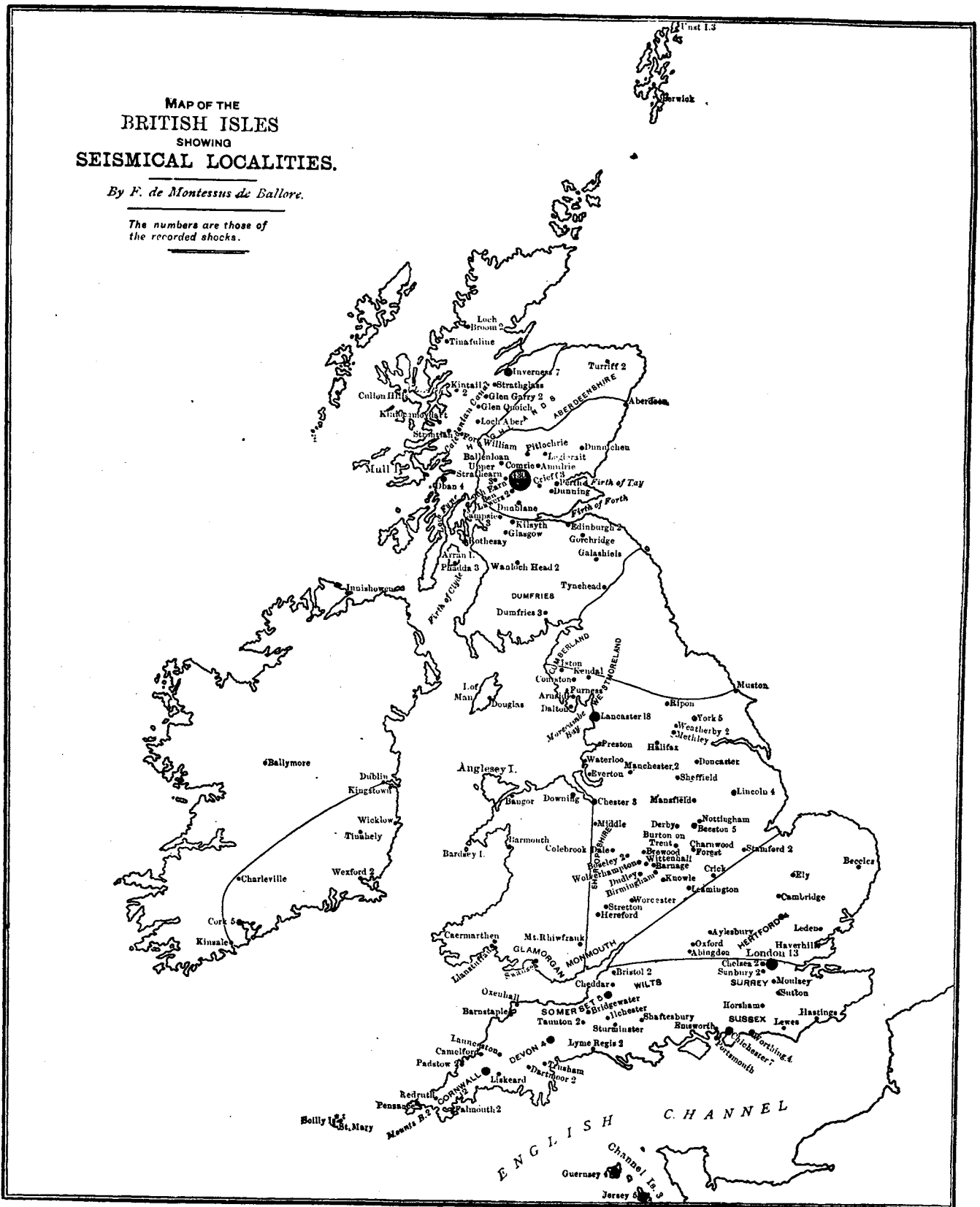


Fig.3. M.F. de Montessus de Ballore's seismicity map presented in 1896

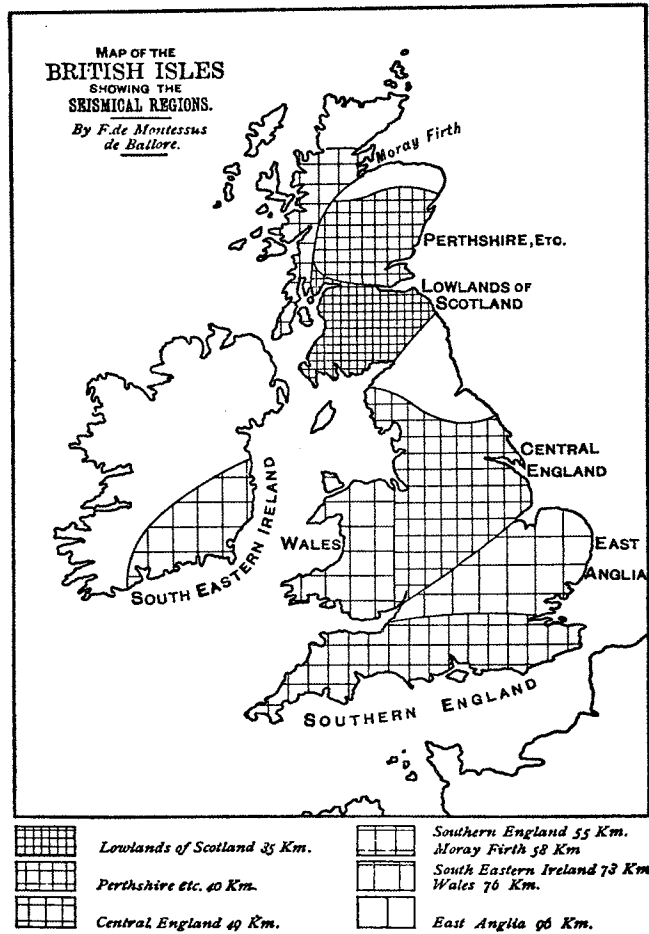


Fig.4. M.F. de Montessus de Ballore's seismic risk map

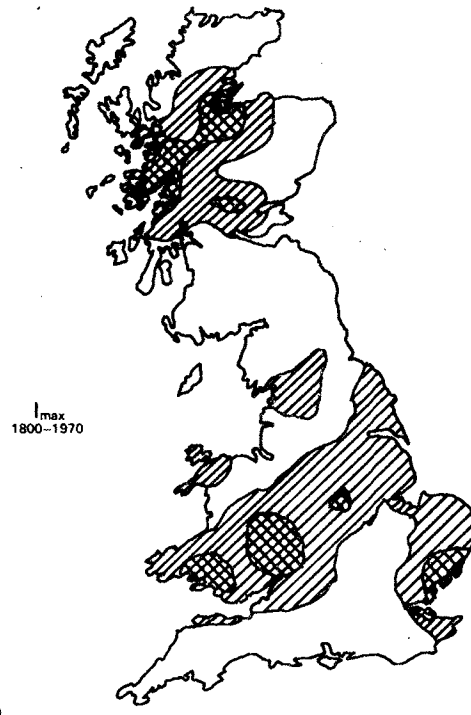


Fig.5. Maximum Modified Mercalli Intensities during 1800-1970: depths of shading give intensities up to V, V-VI, VI-VII and over VII (taken from Lilwall, ref.7)

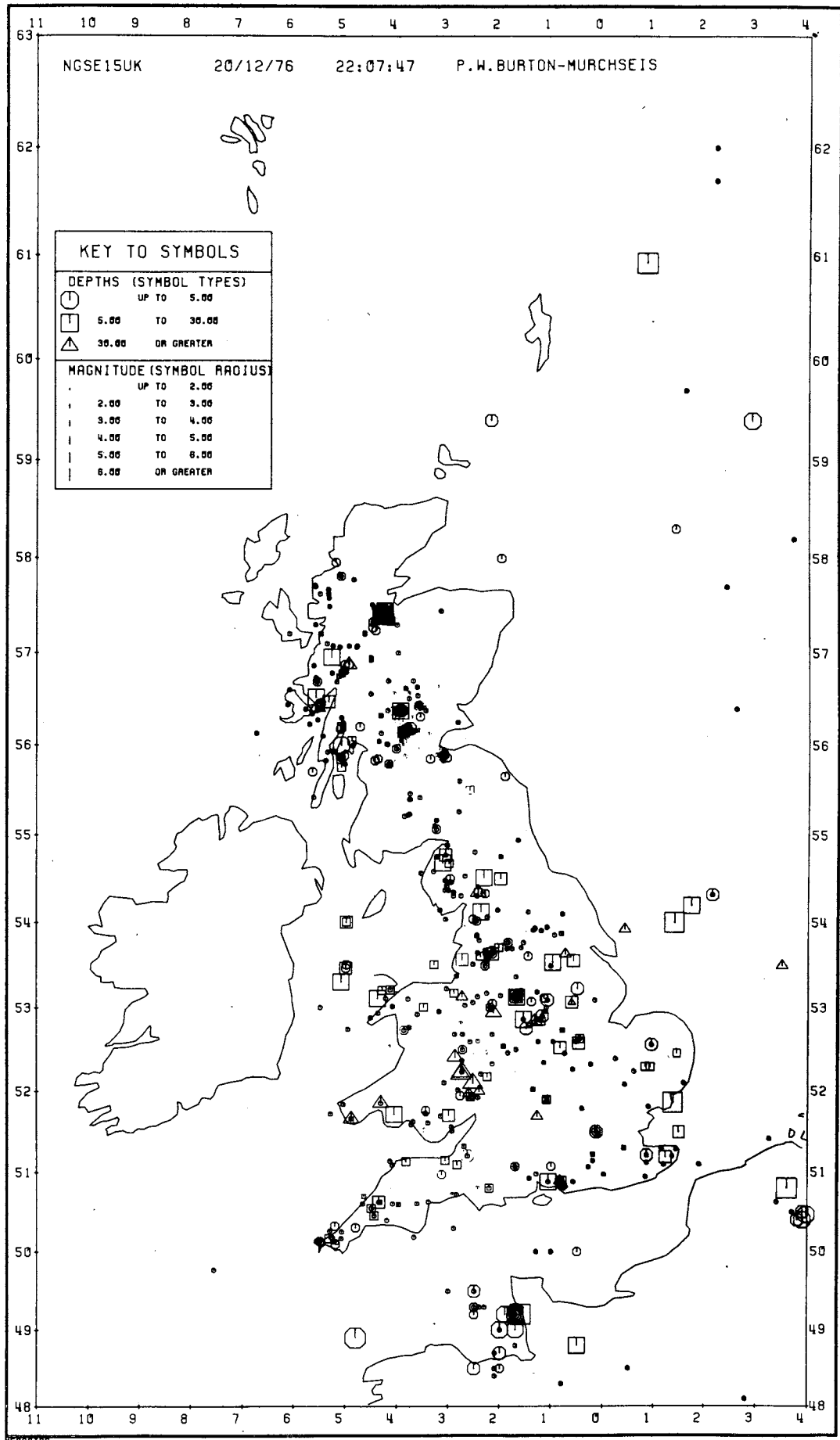


Fig.6. Epicentres of UK earthquakes: many of these epicentres have been determined from macroseismic data and the body wave magnitudes estimated from felt areas

is also assumed that the pattern of earthquake activity is time invariant. If a sufficiently large region is chosen this will be true for historical time spans but not necessarily true for geological time spans. If a large area is subdivided then this assumption of time invariance will break down in some circumstances, for example the earthquake activity at Comrie and Menstrie during the nineteenth century has not continued at the same level indefinitely and is a swarm phenomenon. This difficulty could be overcome by regarding a complete swarm population as one unique and independent event and secondly by analysing the statistics of events within the swarm.

14. A further difficulty is the increasing tendency of man to induce earthquakes, such events could distort the statistics of natural earthquake hazard analysis. It seems that large engineering structures, dams and their contained reservoirs, have a risk of about 1 in 14 of being directly associated with a local earthquake - this is considerably higher than the natural risk of earthquake occurrence. Also it now appears that mining activity is capable of producing earth tremors with locally disturbing intensities.

15. The occurrence rate of earthquakes may easily be described by the cumulative magnitude-frequency relationship

$$\log_{10} N_c = a - b m_b \quad (4)$$

where N_c is the annual number of earthquakes with body wave magnitude greater than m_b , a and b are constants. The constant a depends on the size of the region under study but b is characteristic of the regional seismicity. An annual earthquake extreme within a region is characterised by the value a/b . Adapting Lilwall's results we obtain:

Region	a	b	Annual extreme a/b m_b
All UK	4.13	1.09	3.8
Great Glen	2.9	0.95	3.1
South Wales & Herefordshire	1.1	0.55	2.0
Comrie & Menstrie	6.7	1.95	3.4
Residual	4.0	1.15	3.5

These results are an adequate description of seismicity but there is an element of extrapolation within this table, the magnitude range assigned to the observed earthquakes is $3.25 \leq m_b \leq 5.5$.

A disadvantage of the cumulative frequency approach is that ideally it requires a complete knowledge of all earthquakes down to the threshold of analysis.

16. In a country like Britain where there are great variations in the population density, and macroseismic data does rely on the local population, it is difficult to accept that completeness of the data is homogeneous throughout the

country. To overcome this difficulty annual earthquake extremes may be analysed rather than the entire parent distribution. This procedure has several advantages. An annual extreme is less likely to be influenced by the detection capability of a network than is the entire annual accumulation of earthquakes. Extracting annual extremes from a set of earthquakes will help to overcome the problem of connected events like aftershocks and it will also mitigate against the excessive influence of swarm phenomena. A further advantage is that Gumbel's third distribution of extreme values (ref. 10) allows for an upper magnitude limit to the earthquake population. A cumulative frequency distribution often shows roll off both at the high and low magnitude ranges, this may be explained in terms of the maximum strain energy which may be stored within a region and the brittle yield strength of the local geological structures respectively - but Gumbel's third distribution provides a means of assigning a magnitude value to the upper limit.

17. The general form of Gumbel's third distribution is

$$P_n = \exp \left[- \left(\frac{\omega - m_b}{\omega - u} \right)^\lambda \right] \quad (5)$$

where P_n is the probability that m_b is an extreme value during n years, ω is the upper limit, and u and λ are constants relating to the most likely n year extreme and the curvature of the distribution respectively. The probability P is obtained by ranking the magnitudes in ascending size and the probability for the i^{th} extreme from a total of N samples is:

$$P(m_i) = \frac{i}{N+1} \quad (6)$$

18. Gumbel's third distribution for the entire UK landmass may be obtained (ref. 11) and for five year extremes the distribution is:

$$P_5 = \exp \left[- \left(\frac{5.72 - m_b}{5.72 - 4.43} \right)^{2.22} \right] \quad (7)$$

It should be noted that the relation between annual extremes and n year extremes is

$$P_n = P_1^n \quad (8)$$

and so we have $P_1 = \sqrt[5]{P_5}$. Because Gumbel's third distribution is a better fit to the observed data, it allows for the curvature and upper limit, it is less conservative than the cumulative frequency distribution. Magnitude return periods obtained from equations 4 and 7 for the entire UK give:

Body wave magnitude m_b	Return Period, years	
	Equation 4	Equation 7
4.0	1.5	3.0
4.5	6.0	6.0
5.0	20.0	20.0
5.5	70.0	250.0

Good agreement is obtained between the two distributions over the linear region at intermediate magnitudes but on extrapolation to higher magnitudes the cumulative frequency distribution is more conservative. The upper limit obtained by the method of Yegulalp and Kuo (ref 11) is about m_b 5.7, but I am also investigating an alternative method which considers the uncertainties in these parameters (ref. 12).

Perceptibility

19. It is advantageous to now combine our knowledge of both occurrence statistics and attenuation rates. The radius of perception and felt area for any magnitude and intensity are influenced by the attenuating properties of the local propagation paths. Ideally these propagation paths should be described in terms of their geophysical properties of attenuation. For instance, the attenuation coefficient γ as used by Nuttli (ref. 13) or the specific attenuation factor Q^{-1} used by Burton (ref. 14) for teleseismic work. However, at present our knowledge is limited to the empirical description of equation 1. The occurrence rate is given by equation 7 and we may thus calculate

$$P(m_b | I) \approx P(m_b - \frac{\delta m}{2} \leq m_b \leq m_b + \frac{\delta m}{2}) \cdot P(I \geq I_1) \quad (9)$$

which is the probability that a magnitude m_b earthquake is perceptible at intensity I_1 or greater. The differential probability range around m_b is $\delta m = 0.02$. The results for intensity V to VIII in 'half intensity' steps are shown in Fig. 8, for both a surface and a deeper focus. This approach differs from that of Willmore and Burton (ref. 15) where

$$P(m_b \geq m, I \geq I_1)$$

is calculated.

20. Our knowledge of seismicity within the UK makes this approach desirable. With the exception of the Great Glen, correlations between tectonics and seismicity are tenuous, also the apparently 'aseismic' areas of today may show the greatest strain energy release in the future. So the earthquake population of the UK is treated as a uniformly distributed risk. Combining the statistical risk with perceptibility is also desirable. The asymptotic approach to the upper limit ω of equation 5 might make it appear that a small change in magnitude of a design earthquake could considerably increase the degree of earthquake-proofness of a structure, because the return period would apparently increase by several orders of magnitude. This is a false approach because the upper limit is not precisely known: the combination of risk statistics with perceptibility is one way of overcoming this problem.

21. The structure of Fig. 8, a family of curves peaking just over magnitude 5, now demonstrates the existence of a 'most perceptible' earthquake for the UK. The family of earthquakes with magnitude around 5 may be regarded as a general purpose suite of design earthquakes if the acceptable criterion is that these earthquakes

are the most likely to be felt at any intensity. Structures which may be especially sensitive to particular frequency bands etc. must necessarily modify this criterion. But this method can be modified and applied to other spatial and temporal distributions of earthquakes by suitable modification of equation 9.

22. On the basis of this procedure, it is possible to select a suite of strong-motion data which is characteristic of a region, or in default of this, 'comparable' strong-motion data may be selected from an alternative source.

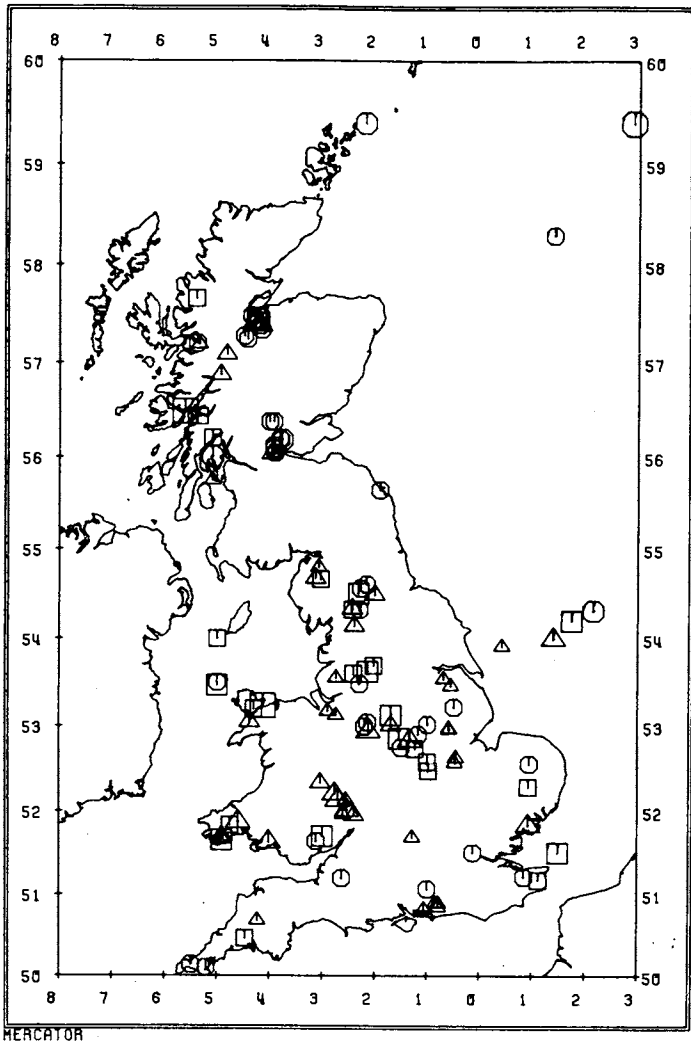
DYNAMICS OF GROUND VIBRATIONS

23. 'Comparable' strong-motion data has been selected for the Inverness area (ref. 16) on the basis of a statistical risk analysis. A preliminary study into the seismicity of the Inverness area was first carried out (ref. 8) to verify our knowledge of the historical record. This local investigation demonstrated a generally high reliability of previous reporters. The exceptions are that it was necessary to relocate one earthquake to the centre of the Great Glen when it had previously been assigned to Inverness and, secondly, one earthquake was removed from the historical record because no acceptable or contemporary documentary evidence could be found. An eyeball cumulative magnitude-frequency distribution fit to the verified seismicity produces

$$\log_{10} N_c = 1.87 - 0.76 m_b$$

and this implies that the 100 year event has magnitude just over 5.

24. There is no strong-motion data presently available for the UK and the best available data set comes from the Californian region of the US. This data set contains 187 three-component accelerograph records obtained from 57 earthquakes. However, the number of relevant records reduces rapidly. Much of the data is generated by the San Fernando earthquake of 9 February, 1971 with magnitude 6.4. There are 41 accelerographs for the magnitude range 5.0 to 5.9 and records from 22 earthquakes with magnitude 5.5 or less. Many of these are recorded at emplacements within the higher floors or penthouses of multi-storey buildings. There are only twelve accelerographs recorded on basement sites from six different earthquakes with magnitude less than 5.5. For all of these accelerograph data a brief site geology is presented by Trifunac and Brady (ref. 17). Most of the earthquakes which occur in the Inverness area of the Great Glen occur within a 10 km range of Inverness and so the San Francisco earthquake of 22 March 1957, with magnitude 5.3 and recorded in a basement at a range approximately 14.2 km is selected as 'comparable'. This accelerogram shows a horizontal peak acceleration of just over 8.5% g which is well within the usually accepted acceleration range for Intensity VII, which may be expected at Inverness. Fig. 9 shows a horizontal component of acceleration for this event.



KEY TO SYMBOLS	
DEPTHS (SYMBOL TYPES)	
○	UP TO 5.00
□	5.00 TO 15.00
△	15.00 OR GREATER
MAGNITUDE (SYMBOL RADIUS)	
○	UP TO 4.50
○	4.50 TO 5.00
○	5.00 OR GREATER

Fig.7. The distribution of earthquakes with a body wave magnitude estimated as 4 or greater

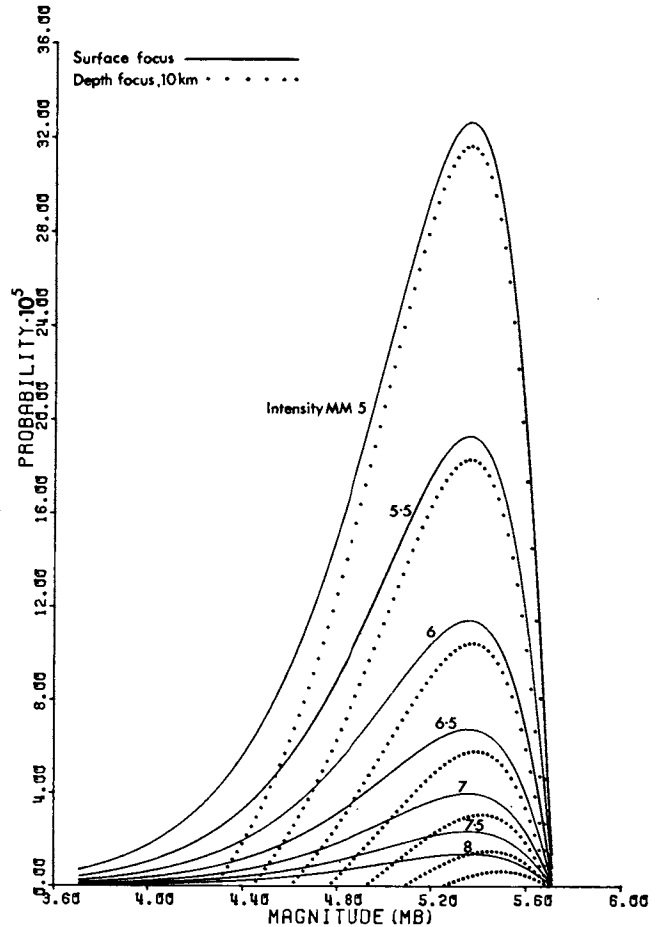


Fig.8. Recurrence statistics combined with an intensity attenuation law peak around magnitude 5 for the UK; this leads to the concept of a most perceptible or hazardous suite of earthquakes; Modified Mercalli intensities and annual probabilities are plotted at each 0.02 increment of m_b

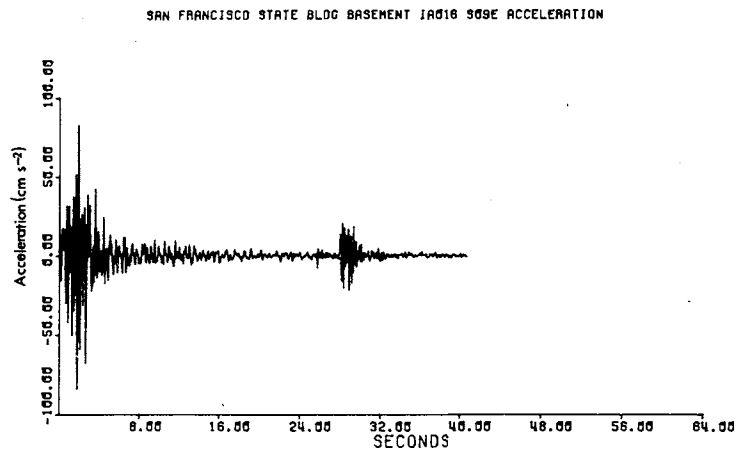
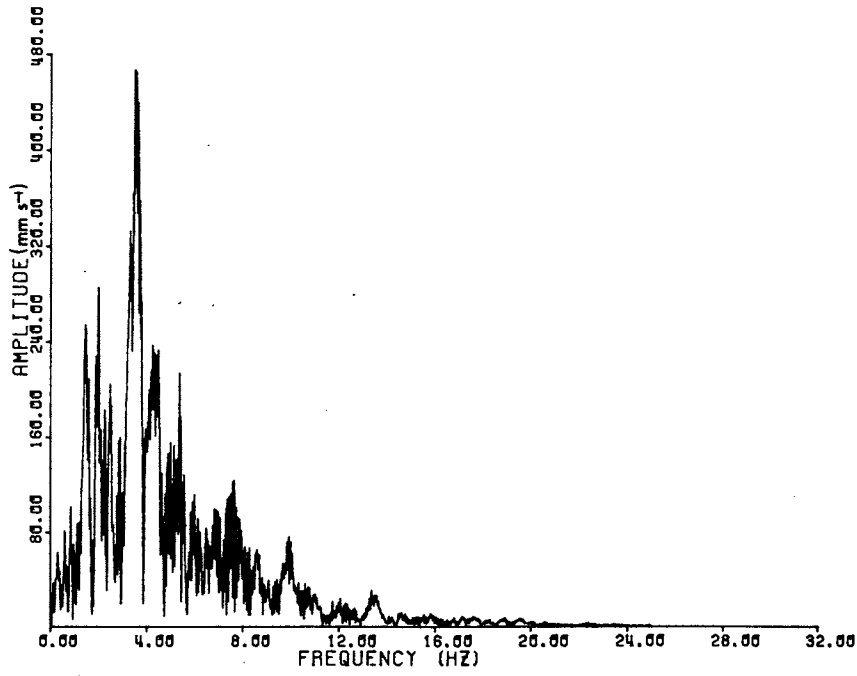
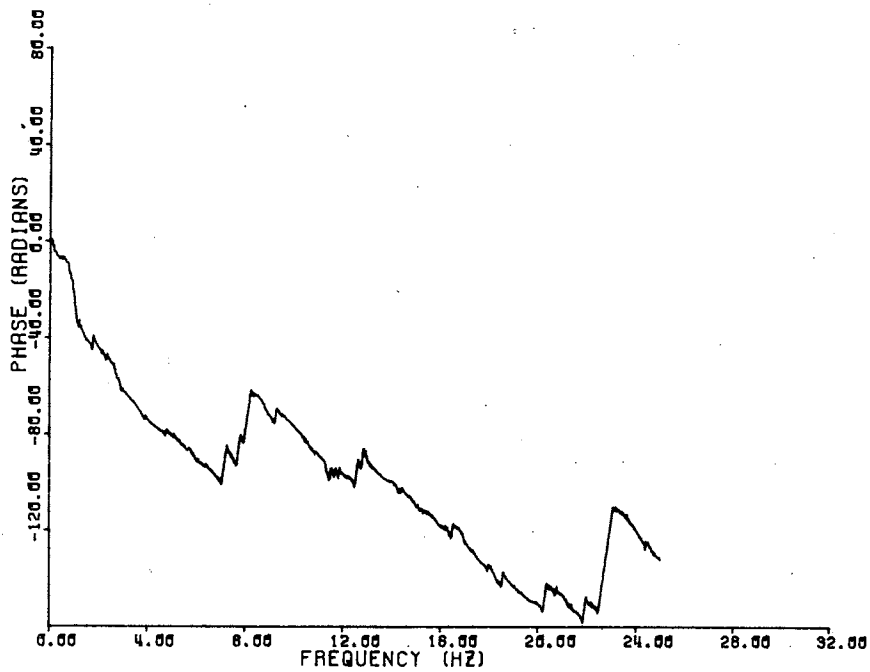


Fig.9. The S09E component of the accelerogram recorded from the San Francisco magnitude 5.3 earthquake of 22 March 1957 recorded at 14.2 km range



(a)



(b)

Fig.10. The Fourier spectrum of the Fig.9 accelerogram data: (a) the Fourier amplitude spectrum with amplitude dimensions of mm s^{-1} ; (b) the Fourier phase spectrum



(a)



(b)

Fig.11. Damage caused by the Colchester earthquake of 22 April 1884: (a) Mr C Harvey's House, Great Wigborough; (b) Rose Inn, Peldon

25. However, there is a growing body of opinion which suggests that near-field earthquakes generate high accelerations; Bufe et al (ref. 18) have recorded 70% g from earthquakes with magnitude less than 5.3. In view of this the acceleration properties of the Parkfield earthquake of 27 June 1966 and magnitude 5.6 recorded at Temblor are relevant. Estimates of the range for this recording vary from about 23 to 60 km. The peak horizontal acceleration observed on this accelerogram is about 30% g.

26. This analysis indicates that accelerations of at least 10% g may be considered for particular design purposes within the UK.

Time V frequency domains

27. Given a time series for ground acceleration at a site, or alternatively the velocity or displacement, it is often useful to cast this into a frequency domain analysis. It is vital to realise that there is a duality of time series and Fourier representations which is exact. Figs. 10(a) and (b) show the amplitude and phase spectra obtained from Fig. 9 using a Fast Fourier computer program written by Burton and Blamey (ref. 19), the amplitude and phase data completely define the spectrum of the original time series. This technique allows the opportunity of investigating the frequency at which the seismic energy reaches its maximum within a time series, whereas the time series itself is more appropriate for estimates of duration of the ground vibration.

EARTHQUAKE DAMAGE

28. The previous analyses of this paper involve wide ranging concepts and techniques, some of which are complicated. But it is worth realising that the larger British earthquakes are felt over considerable areas and do cause structural damage. The Inverness earthquake of 13 August 1816 was felt in Edinburgh and over an area of roughly 130,000sq km and the epicentre is in an area of known seismicity.

29. On the 22nd April, 1884, a large and damaging earthquake occurred near Colchester. Newspaper extracts and contemporary photographs depicting this event have been published (ref. 20) and a popular history written by Haining (ref. 21). This earthquake was felt 180 miles north in Altrincham, Cheshire, damaged over 1000 buildings, and there is evidence that the earthquake caused fatalities. Figs. 11(a) and (b) show examples of the damage caused by this earthquake to local buildings and amenities.

CONCLUSIONS

30. The facets of an analysis of seismic risk are varied, but it is possible to examine the limited data presently available and to assign a statistical risk to earthquakes of the UK and to seek 'comparable' strong-motion data from elsewhere. Damaging earthquakes do occur in the UK and it is likely that accelerations reach, and may exceed, 10% g.

ACKNOWLEDGEMENTS

31. I wish to thank Mr. Seabrook and the West-cliff Group of Companies for access to photographs of damage caused by the Colchester earthquake. This work has been supported by the Natural Environment Research Council and is published by permission of the Director of the Institute of Geological Sciences.

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4. Vibration problems in civil engineering

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Engineers may need to record vibration for many reasons including the necessity of complying with legislation designed to protect the environment and the obligation of preventing damage to buildings. This paper describes the type of records which can be made and suggests reasons why engineers may require vibration recordings to be made before, during, or after their operations.

INTRODUCTION

1. One of the primary objects of this conference is to acquaint the average Engineer, who generally admits only to a passing knowledge of vibration techniques, of the capabilities of modern vibration recording instruments and to show how they can assist him in dealing with problems concerning ground and structural vibration. A sophisticated treatment of the subject is not possible in the time available but other papers will demonstrate the uses of various vibration recording instruments and the value and interpretation of the records thus obtained.

2. It is to be hoped that Engineers and others with varying interests will have been attracted to attend the conference, and for the those few who may not be familiar with the terminology used in vibration engineering, the basic parameters and their relationship with each other are set out in Fig. 1.

3. There are likely to be many seismologists amongst those at the conference and although the engineering approach to soil dynamics may appear to be comparatively unsophisticated, I hope that our problems and methods of dealing with them may be of interest and perhaps spark off some new thought.

4. Other papers will demonstrate how vibration recordings may be made and discuss the interpretation and analysis of the vibrograms. As an introduction to these papers I shall discuss the reasons why we should want to make such vibration recordings in the first place. Some general reasons for recording are:

1. Preservation of the human environment
2. Prevention of structural damage
3. Ensuring compliance with the law
4. Collection of evidence to support complaint or defence in the Courts
5. Compliance with insurance requirements
6. Collection of design data
7. Furthering research.

Recording systems

5. There are two distinct types of vibration recording. Some instruments, vibrographs or seismographs, are designed to record relatively short samples of vibration which are true vibrograms yielding a record of any one, or all three, of the major parameters: acceleration, particle velocity or displacement on a time base from which the frequency can be deduced. Other instruments, vibration monitors, operate on a long term basis recording only the peak values of the chosen parameter on very slow moving recording medium which is incapable of resolving the frequency of vibration. Variations of the latter system give only a digital display of peak values or, alternatively, trigger an alarm system when a preset peak value is exceeded.

6. Whilst the concept of displacement varying with time is most easily visualised, it is not the most useful parameter nor the most easily measured with modern instruments. Acceleration recorded by crystal accelerometers or particle velocity by geophones, or from integrated accelerometer output, is more commonly used today. Particle velocity is, arguably, the most useful parameter since both human beings and structures respond to it in a manner almost independent of frequency.

Preservation of human environment

7. In recent years great emphasis has been placed on environmental considerations as they affect both people and the buildings they occupy. The impact of this is now being felt with increasing severity not only in the manufacturing industries but also on civil and structural engineering works. In most cities there is never a time when construction of major buildings or roads is not taking place somewhere within the city boundaries. With the anticipated revival of our economy, the spate of new building works will aggravate the environmental problem.

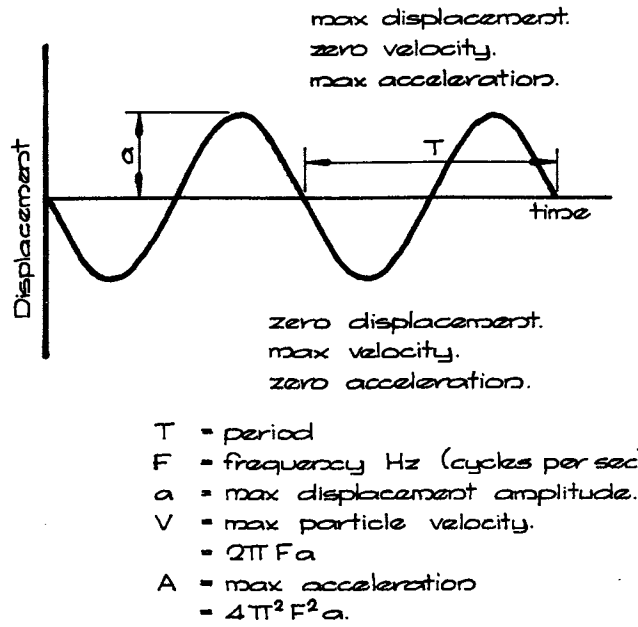


Fig.1. Vibration terminology

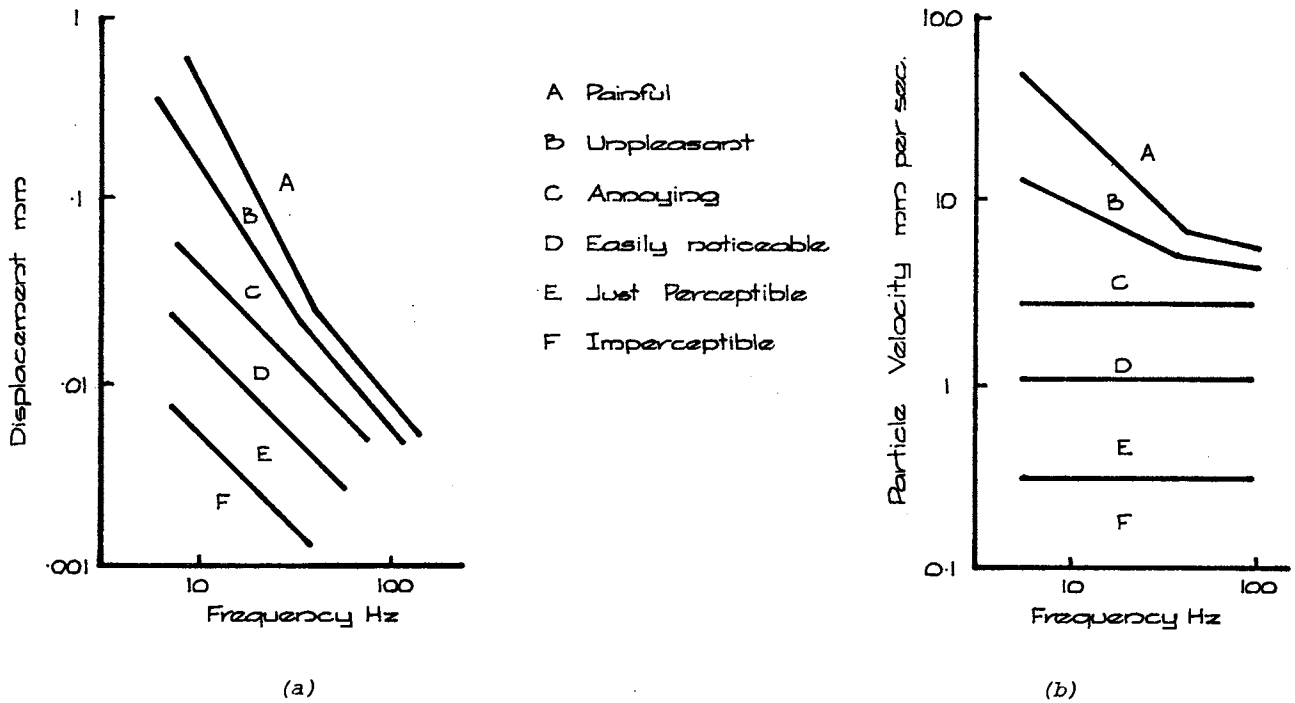


Fig.2. Human perception (Reiher-Meister)

Human perception of vibration

One of the first serious attempts to investigate human perception of vibration was published in 1931 by Reiher and Meister (ref 1) who subjected individual persons to vibration of varying displacement amplitude and frequency. The subjects were asked to classify the sensation of various samples of vibration and the resulting "ReiherMeister Scale of Human perception" Fig. 2a is still accepted today as a good guide to the intensity of steady state vibration. Other scales are given in the bibliography (ref 2).

9. Human reaction to intermittent or transient vibration is rather more difficult to assess but generally falls into a classification one grade below the steady state condition of equal displacement amplitude.

10. In Fig 2b the ReiherMeister scale is re-plotted in terms of particle velocity showing the resulting independence of frequency at moderate intensities.

The law relating to vibration

11. Since 1936, action to prevent noise and vibration nuisance could be taken under the provisions of the Public Health Act. In 1960 the Noise Abatement Act, which also applies to vibration, became law and in 1963 the Wilson Committee on Noise published its findings and recommendations. But it was not until 1976 that the provisions of the Control of Pollution Act 1974 actually became enforceable. In addition to these statutory controls of noise and vibration, action to prevent such nuisances can be taken under Common Law.

Control of Pollution Act 1974

12. This Act has probably done more than any other measure to bring home to civil and structural engineers the serious view taken by Government on the impact of noise and vibration from building sites on local residents. Although the Act is at present commonly assumed to apply only to noise, it is equally applicable to vibration vide Clause 73(1) which simply states "Noise includes vibration". Under the provisions of the Act a Local Authority may issue a "notice" demanding that any industrial vibration which it considers to be a nuisance should be abated within a specified time. On expiry of this period, the Local Authority may seek an injunction in the Magistrates' Court or in the High Court. To provide a defence against such an action, it is clearly necessary to be able to present evidence in the form of well documented vibration records to show that the vibration is either insufficient to be classified as a nuisance, or that the "best practicable means" have been taken to reduce the vibration to a minimum.

13. To avoid the threat of injunction, a building contractor may, prior to the commencement of the work, apply to the local Authority for a "consent" to the methods of construction

which he proposes to use. If satisfied that no unreasonably excessive vibration will result from the use of these methods, the Local Authority will issue a "consent" which may contain certain conditions such as limits of vibration intensity at the site boundaries. The Local Authority is also, of course, empowered to refuse "consent" to the methods proposed.

14. A "consent", when issued, is a defence against any legal action taken under the provision of the Act at a later date to stop the specified work on the grounds of excessive vibration.

15. In order to obtain a "consent" the contractor may have to be able to specify the vibration intensity arising from the operation he wishes to carry out. In many cases these will clearly be insignificant but when pile driving, by impact or vibration, and when blasting or using dynamic consolidation or other vibration generating operations, the Local Authority will certainly require a specification of the Contractor's proposed vibration limits. At some stage vibration measurements must provide this data so that sufficient experience will be built up to enable reasonably accurate prediction to be made.

16. Almost literally on the other side of the fence, the Local Authority will need to supervise, and, in some cases, to enforce adherence to the vibration limits which may have been included in a conditional "consent". In this case it is probable that a monitoring procedure would be adopted to yield a continuous recording of peak values of vibration intensity at the site boundaries.

Summary proceedings by occupiers of premises

17. Section 59 of the Control of Pollution Act supercedes the provisions of the Noise Abatement Act 1960 and permits a Magistrates' Court to act upon the complaint of any occupier of premises concerning vibration nuisance. The old Noise Abatement Act required the complaint to be made simultaneously by at least three occupiers of premises. The Court can order the abatement of the nuisance and prohibit its recurrence or require any specific remedies to be executed with a specific time.

18. It is, of course, necessary in these cases to show that the vibration which is the subject of the complaint is sufficiently great to be considered as a legal nuisance, and vibration recordings are invariably necessary for this purpose. Conversely, vibration records will be required as evidence in the defence against such a claim.

19. It is also a defence under this section of the Act to show that, despite the nuisance caused by the vibration, the "best practicable means" have been taken to mitigate the effect of the vibration. Vibration measurement can provide powerful evidence of reduction of vibration intensity when the "best practicable

means" have been employed.

Common Law

20. Any person affected by vibration can take individual action in the High Court to restrain a person or organisation from causing nuisance by excessive vibration. The plaintiff must show that the vibration is such as to materially interfere with his comfort and enjoyment of the premises which he occupies. It is important to realise that in Common Law actions there is no defence of "best practicable means" nor of public interest. Neither is it a defence to show that the vibration existed in the locality before the plaintiff took up residence.

21. The only defence against a common law action is to show that the vibration intensity is insufficient to be classified as a nuisance in the context of the existing environment. The only exception is the case where Parliament has specifically exempted or authorised the operations which are the subject of complaint.

22. Cases of nuisance brought before the Court can only be established or defended by accurate and well documented vibration recording and monitoring which should obviously be carried out by an engineer independent of both parties. Subjective assessment of vibration intensity is seldom admissible in court, although when practicable the judge may wish to experience the nuisance personally. However desirable this may be, the disturbance often occurs only seldom and reaches maximum intensity at unpredictable times. In such cases long term peak intensity monitoring is essential.

Prevention of Structural Damage.

23. Damage to buildings can occur from internally generated vibration or from vibration transmitted through the ground and foundations. The damage may be classed as minor (some times termed "architectural damage" or "accelerated ageing") or major (structural).

24. Minor damage is confined to cracks in plaster finishes, paint films and other blemishes such as would be expected to occur in any building in the course of time as it gets older.

25. Major damage includes cracks in walls and other structural or load bearing units.

26. Damage to a building may be caused by the vibration of the whole structure or by vibration of one part, such as a ceiling, relative to the whole. Damage from vibration may also be caused indirectly by settlement of the buildings due to consolidation of loosely compacted granular soils or to slurring of silty soils in the presence of water as well as by many other causes.

27. Safe levels of structural vibration will, no doubt, be discussed at length in

other papers, and structures may be protected from damage by recording the vibration to ensure that such levels are not exceeded.

Protection of services

28. In some cases ground vibration can be a hazard to buried services. Whilst piped services can generally tolerate quite severe ground vibration, old brick sewers and culverts may have to be treated with special care.

Protection of trade processes

29. A sure way of attracting an injunction against vibration is by adversely affecting trade processes conducted by firms adjacent to a building site or other vibration source. Processes such as precision metal machining, laboratory work, photographic processing, printing and many manufacturing operations can be extremely sensitive to vibration. Any disturbance adversely affecting the trade of a neighbour is unlikely to receive much sympathy in the courts.

30. It is advisable, therefore, before embarking upon any vibration generating operation to ensure, during an initial site survey, that no such disturbance to trade will occur. If such a problem is likely, the vibration tolerances of the process must be established, if necessary by vibration recording, and the site operation designed not to exceed these limits.

Vibration from civil engineering works

31. Operations such as impact and vibratory pile driving, demolition, blasting, tunnelling and quarrying can frequently give rise to vibration of sufficient intensity to cause personal distress to people close to the works and even to cause structural damage. Vibration measurement is the means by which such effects can be controlled.

Piling

32. It is frequently possible to establish the probable intensity of vibration from previous vibration recording on other similar sites, but in important cases it may be necessary to record its vibration from a test pile on the actual site concerned. When driving in close proximity to a building, it may be difficult to estimate the response of the structure and in such a case a closely controlled vibration test on several piles may be necessary prior to approving the method.

33. As a result of the prediction of vibration intensity on the basis of previous vibration recordings, it may be possible either to give blanket approval to the proposed piling methods, or alternatively to zone the work so that more expensive but vibration free foundation methods are confined to smaller areas where piling would be hazardous.

34. It will be appreciated that there is no sharply defined boundary of vibration intensity above which damage occurs and below which it

does not. The limits of "no damage" and "certain damage" are spaced widely apart with a large zone of variable risk in between. The results of vibration recording generally enable a "degree of risk" to be allotted to the proposed operations when the prediction indicates that safe limit is exceeded but there is no certainty of damage.

35. It is always advisable to record the vibration on site at the commencement of the site operations to check the accuracy of the predictions and also to establish a monitoring procedure which will record all peak levels throughout the period of the disturbance. Not only does this ensure that any sudden variation of vibration intensity will be evident to the engineer so that appropriate measures can be taken, but also ensures that the evidence of recorded vibration is available to combat unjustifiable claims of damage to property.

36. The Contractor's insurers often require that the vibration shall be monitored during the contract. Sometimes a vibration limit is specified which must not be exceeded, but quite often no limit is specified, in which case the vibration monitor record can only be used to assess the merits of any claim for damage. Generally it is better to place some limit on the permissible monitored vibration so that the degree of risk in exceeding the limit may be accepted by the interested parties before work proceeds.

Tunnelling

37. Tunnelling operations involving blasting are often carried out immediately below buildings in urban areas, and in such cases it is essential that close control is maintained over the level of vibration. Individual blast vibration records must be taken to keep control on the blasting techniques to limit the vibration to a minimum.

38. A technique of leap frogging monitor instruments down the line of a tunnel as the face progresses can enable a check to be kept of the peak intensity throughout the job when suitable typical premises are available in which to house the instruments.

39. Since tunnelling operations are of a transitory nature, no attempt is usually made to keep vibration below the threshold of human perception; indeed this would be impossible in most cases. The limit of permissible vibration is normally set to prevent damage to buildings. Major damage is to be avoided at all costs and minor damage, which is to be repaired at the contractor's expense, is kept to a minimum. Properly designed vibration recording enables this to be done efficiently and also combats unjustified claims for repairs to long standing defects in buildings.

Quarry blasting

40. Quarry blasting, unlike tunnelling, is a comparatively static operation which continues for years on end and gives rise

to bitter complaints by local residents resulting in many court cases. The courts have occasionally imposed limits of vibration intensity at the boundaries of the quarry or at the nearest inhabited property.

41. Such limits have been determined as a result of site vibration measurements and once set by the courts, the quarry owners face a charge of contempt if they are exceeded. Generally the quarry owners decide to set up their own vibration recording or long term monitoring procedures to ensure compliance with the orders of the court. In addition it is not unknown for the residents or the Local Authority on their behalf, to set up their own monitoring station to ensure compliance.

Data collection

42. British Standard Code of Practice C.P. 2012 on "Design of foundation for reciprocating machinery" has introduced into general use a method of calculating the dynamic behaviour of machine foundations which is based on the "dynamic coefficient of uniform soil compression" (Cu). This coefficient determines the effective dynamic spring rate of the elasticity of the soil.

43. There are several methods of determining this coefficient. One of them is based on the experimental determination of the speed of propagation of surface waves in the soil by measuring the frequency and phasing of sinusoidal vibration at two distances from a source in the ground. Any multi channel vibration recorder can be used for this operation. At the same time the rate of attenuation of vibration amplitude with distance can usefully be measured.

Plant vibration

44. It has been mentioned previously that vibration records are necessary to determine the dynamic behaviour of plant. Recently vibration records on a piling system showed that optimum driving rates for vibrating piles were achieved by tuning the driving frequency so that pile and the surrounding soil were vibrating in antiphase thus creating maximum shear forces at the pile soil interface.

45. It was also very clearly demonstrated that severe ground vibration, up to 300% greater than necessary, was generated by vibratory pile driving tuned to the resonant frequency of the pile soil system.

Stress measurement

46. Stress measurement is often possible by means of vibration measurement. The dynamic stress induced in structural members such as beams, bridge decks, towers and chimneys can relatively easily be calculated from measured vibration amplitude and mode shape recordings.

Tie bar stress measurement

47. The static stress in tie bars has recently been calculated by measuring the "twang" frequency of the bar and using this to

calculate its tension in a similar manner to the variation of tune of a violin string.

Pile Testing

48. During the last few years, an ingenious pile testing method has been devised which, by inducing end to end sinusoidal vibration of a completed concrete pile within the soil and recording its response to a frequency sweep, can deduce with some accuracy the integrity of the pile, its length and bearing capacity. In this case the vibration recording instruments consist of an automatic plotting system for particle velocity of the pile head and of the frequency of applied vibration. The properties of the pile are deduced from the shape of the instrumental plot.

Conclusion

49. In these and many other ways, vibration recording can become a useful, and in many ways indispensable tool for the engineer. In these days of environmental awareness on the part of Government and the public it is necessary that

the effects of vibration should be fully appreciated by engineers some of whom have not up to now needed to concern themselves unduly about it.

50. Lawyers are producing more selective legislation, manufacturers are producing new, more flexible and easily handleable instruments, researchers are defining better standards to help interpret the records, so let us hope that project engineers, perhaps initially with the help of vibration specialists to advise them and to set up vibration surveys, will learn how vibration can be recorded and when and why it should be.

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Discussion on Papers 1-4

MR O'NEILL (Paper 4): My paper is intended mainly for engineers rather than for seismologists, but I hope that it will be of interest to the latter and perhaps plant the seed of a new idea in their minds.

Although my paper is taken as read, I would draw your attention to the seven reasons for measuring engineering vibration which I have suggested. These are the most common reasons for vibration recording which may be either short term analytical recording, or long term monitoring of one or more parameters.

Sophisticated instrumentation may be used to record vibration for later detailed analysis, but very often field instruments are required which will yield a vibrogram for immediate assessment on site. In order to illustrate the uses of such instrumentation I will present some case histories.

During the excavation of the sewer tunnel beneath Dublin city, explosives had to be used in some areas, one of which was immediately below a gas main. Vibration records were taken simultaneously with dynamic strain recordings to establish the relationship between vibration intensity and pipe stress. Thereafter, the integrity of the pipes was confidently preserved by vibration monitoring.

Piling, near a factory extruding plastic insulated submarine cable, threatened the quality of the finished product. Testing was only permitted for four minutes on Monday morning and four minutes on Friday evening, at the beginning and end of the non-stop weekly production run. Nevertheless, by careful planned piling vibration testing during two of these periods, the malfunction level of the cable extrusion plant was established, and on the basis of this data the site was zoned to permit conditional and unrestricted piling to proceed in specified areas at specified times.

In tunnelling and quarrying operations, vibration recording can be used to establish the relationship between weight of explosive and distance from the blast. Comparison with safe structural limits can then determine the safe weight of explosive which may be used at any location.

Heavy vibration of floors in factories can often cause concern to the occupants of buildings, and to designers. Vibration records can determine the oscillatory deflection of the floor and the stresses in concrete and steel can be calculated from this data.

A similar technique was recently used at St

George's Theatre in north London. The theatre is a converted church of octagonal shape, dimensionally very similar to Shakespeare's Globe Theatre and hence very suitable for Shakespearian productions. Unfortunately a tie bar across the proscenium arch obstructed actors playing in the stage balcony. Before removal of the tie bar, it was necessary to determine the load it carried so that suitable alternative structural arrangements could be made. The load was determined by recording the natural frequency of transverse vibration of the bar by plucking it like a violin string. The 'twang' frequency together with its dimensions and mass enabled us to calculate its load. Strain gauge recordings, as it was de-stressed, confirmed that our calculations had an error of only 10%.

A recent exercise on Kariba Dam serves as an illustration of oscillatory recordings other than that of physical vibration. On completion of the new power station on the north bank, the Zambian side, the massive coffer dam surrounding the intake tunnels upstream of the main dam had to be demolished. The coffer dam was charged with explosives and the water each side equalized. In order to confirm the predictions by model testing of the hydraulic shock pressures due to the blast on the intake structure and gates, it was necessary to record the shock pressures under water. It was also desired to establish the efficacy of a form of underwater bubble curtain in filtering out the hydraulic shock. The hydraulic pressures were recorded by piezo-electric tourmaline gauges at a depth of about 30 m of water in five locations. The amplified signal from the gauges was recorded both on FM and direct-recorded tape on ten channels and later played back into a UV recorder on an extended time base to enable a visual comparison of pressure amplitude and phasing to be made of each location, together with the time history.

This and many other types of vibration and other oscillatory recording are now available to the engineer who, even if he lacks the technical ability to carry out the instrumentation himself, should be aware of its potential (and its limitations) when the occasion arises.

DR H. SPLITTGERBER (Landesanstalt für Immissionsschutz, Essen): Vibration records of man-made vibrations are often performed as visible traces on chart paper. As evidence for local authorities, courts etc., such records are of value only if an accurate calibration is made, especially

for the sensitivity of the amplitudes. Calibration of velocity pick-ups under field conditions often is somewhat troublesome. Is there convenient calibration equipment available? The calibration procedure should include the pick-up. Are tape records acknowledged as evidence by courts? Manual interference can produce errors to attenuations.

MR O'NEILL: Whenever I have presented evidence of vibration intensity in court it has always been accepted without question. When I take visual vibration records which are likely to have to be presented as evidence, I always include a calibration signal within the vibrogram. This calibration signal includes the amplifiers but excludes the transducers. The latter are generally found to be so stable that only occasional laboratory calibration is necessary.

Wherever possible, in cases being prepared for hearing in the courts, it is advisable to have a witness to the recording procedure.

I cannot comment on the submission of tape recordings as evidence since I have never attempted it, but I think it would be less acceptable than a visual vibrogram.

DR P. SRINIVASULU (Structural Engineering Research Centre, Adayar, Madras, India): In Paper 2, at the end of §2, the author has stated that there is a general acceptance for recording peak velocity (in the frequency range 1-100 Hz) as a measure of structural damage. I would request Dr Skipp to elaborate on the special significance of velocity measurement in comparison with acceleration or even direct displacement measurement. The IS 2361-1974 which is a 'guide for the evaluation of human exposure to whole body vibration' gives acceleration criteria for this purpose. Also, I have observed in an ambient vibration study that velocity and acceleration spectra obtained at the same site from field measurements did not show the same peaks or the same individual frequencies. This seems to bring out the importance of choosing appropriate parameters for measurement for different situations.

In Paper 4, Mr O'Neill has brought out the various implications of vibration which necessitate field measurements. It is interesting to read the legal aspects of the problem which are the same in all countries. The only way of avoiding the problems of going to court on grounds of 'excessive annoyance', which in most cases turn out to be baseless and unqualified, is for the local authorities to stipulate standard criteria in terms of acceptable limits in different regions - residential, commercial, industrial and so on. I was myself involved in a consultancy problem in which a printing press owner approached us for a certificate showing that the printing presses, when moved from one location to another which was predominantly residential, would not cause excessive vibration nor cause annoyance to people living in houses nearby. Apparently the local authority wanted the company to get such a certificate before a permit could be given for the transfer of the presses. Based on our investigations at the two sites, we gave them a report that if the local authority endorsed our suggestion regarding

acceptable vibration levels at that location, the presses might be moved without fear of annoyance, provided some secondary measures were taken to ensure attenuation of vibration energy with distance from the source. With the ambient vibration level measured at site, and knowing the vibration limit specified, it should be possible in most cases to design a suitable isolation system to meet the requirements.

Research is in progress in phases at the University of California, Berkeley, involving dynamic tests on reinforced concrete frames for studying their inelastic behaviour. The notable feature of this test programme is the use of the 20 ft x 20 ft shaking table, and the automatic system of data acquisition and data analysis using sophisticated electronic instrumentation. Tests on the dynamic behaviour of prototype structures like high-rise buildings have recently been carried out at the California Institute of Technology, Pasadena, and the University of California, Los Angeles. Building shakers with associated driving equipment were used for exciting structures in this test programme, while for the measurement of response a transducer-preamplifier-recorder system was used in most cases. In my opinion, resistive or inductive (seismic) types of accelerometer may be preferred in such tests mainly on account of ease of field calibration just before the test is started and again to verify the same after the test is completed. During my visit, a model study on a complex bridge structure was under way at the University of California, Berkeley. The seismic behaviour of the bridge was studied in order to establish the validity of the analytical model used in the theoretical analysis.

DR WILLMORE (Paper 1): The shift in spectral peak when one moves from one parameter to another arises from the process of multiplication or division by frequency as one changes from one parameter to another. The point can be illustrated by referring to the response curves of the simple pendulum, in which the maxima for acceleration and displacement response are shifted in relation to the symmetrical maximum of velocity response. We see how this shift arises by fitting tangents with gradients of plus or minus one to the curves of the central diagram.

DR SKIPP (Paper 2): Dr Willmore has lucidly explained why peak velocity and peak acceleration do not necessarily occur at the same frequency. Particle velocity as a single-parameter criterion has the attraction that for frequencies of structures near to dominant frequencies of input the response is symmetrical as Dr Willmore has outlined. There is also a useful relationship in simple oscillating elements between peak velocity and peak fibre stress.

MR R.G.T. LANE (Sir Alexander Gibb and Partners, Reading): The combination of occurrence statistics with perceptibility, as shown in Fig.8 of Paper 3, gives a good visual and useful illustration of earthquake risk for the UK. Other environments are conditioned by different geological features - in one case proximity to a major fault, in another a zone of activity in which there is

risk of activity at any fault. It would be interesting to know if Dr Burton has applied a similar method in other cases. A cut-off with zero probability does not seem reasonable for other cases.

DR BURTON (Paper 3): I have not yet applied this technique elsewhere although it is clearly possible to do so. The present application to the UK is ideal for assessing an average risk without considering local variations which are evident on zoning maps. Clear tectonic features such as the San Andreas lend themselves to analysis by Cornell's technique; however, the present technique could be modified to fit this new situation. This would lead to estimates of ground motion perceptibility at different perpendicular distances to the linear fault. Secondly, in an area which is heavily faulted the probability of earthquake occurrence may be considered equally distributed in space and the technique applied directly. Thirdly, Knopoff has demonstrated that an upper magnitude limit is a physical necessity to ensure that the rate of strain energy release remains finite. Analysis of historical data does generate different upper limits for different regions; however, this assumes that the temporal pattern of occurrence is invariant. Invariance may be true for historical time spans but not necessarily true for geological epochs, so prediction over historical time spans with direct economic consequences will probably be correct but longer predictions will require other considerations - for instance the movement of plate boundaries.

DR G.K. WESTBROOK (Department of Geological Sciences, University of Durham): What criteria does one use to decide on the bounds of the area from which the statistics concerning earthquake occurrence are to be derived?

DR BURTON: The statistics are not solely directed at estimating the probability of earthquake occurrence but are designed to estimate the probability of perceiving particular levels of ground motion associated with earthquake occurrence, usually within economic time spans. This has two consequences. First, because the UK is in a mid-plate position it is remote from the major earthquakes which occur at plate boundaries. Typically a magnitude 8 event is perceived at the threshold of damage, intensity V or VI, to a range of about 750 km, whereas a magnitude 6 event is similarly perceived to a range of only about 130 km. There is little evidence which may be usefully analysed of earthquakes outside the UK being perceived at damaging levels within the UK, the exceptions mainly being associated with earthquakes in the North Sea. The second consequence is that most of the historical data on UK seismicity is macroseismic, and naturally this implies most of our present knowledge is for earthquakes with epicentres within or close to the land mass; this is a natural limitation on the data presently available. So the criterion is one of perceptibility, and is limited by the geographical extent of the available data for a island situation.

DR WILLMORE: I think the point is that if one extrapolates return periods with no limit on mag-

nitude, and also extrapolates intensity-magnitude-distance relationships, one can come to the absurd conclusion that hazards anywhere in the world would be dominated by events of enormous magnitude at very great distances. If, however, the earthquakes in the area surrounding the region of historical experience have an upper limit on magnitude which is similar to that of the actual area of survey, and not too far above the actual extreme magnitude of the historical time span, the fringing effects will decay fairly rapidly in respect of earthquakes outside the boundary.

DR SKIPP: Procedures have been suggested to test the completeness of a statistical sample from a given region¹ but there is always a 'trade-off' between expanding the region for statistical purposes and overstepping the tectonic controls. These tectonic controls are extremely difficult to define in practice. On a very coarse scale it may be possible to establish significant differences in the cumulative magnitude-frequency relationships between different so-called seismotectonic provinces but it does seem that over-refinement is often carried out without proper testing of the statistical significance of the apparent differences between such relationships.

MR J.H. KUEHN (BSK Laboratories Ltd, Hounslow): Would someone please explain methods of earthquake magnitude scaling? I have not been able to find an explanation of Richter scale anywhere.

DR WILLMORE: Historically, the concept of 'size' or 'magnitude' of an earthquake was determined from its macroseismic effects, notably the area over which it was felt. In 1935, however, Richter produced the 'instrumental earthquake magnitude scale', in which the magnitude M_L of a shallow local event was determined from the maximum trace amplitude of a standard Wood-Anderson seismograph, normalized to a standard distance. Subsequently, the basic concept was extended to earthquakes at all distances and depths by using the ratio of ground amplitude to wave period for surface waves and for various body wave phases. These give magnitudes M_S , m_b , M_{py} etc.

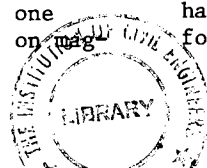
For a long time, efforts were made to relate all estimates of the magnitude of a given event to a single 'unified magnitude' m , which would be a measure of the energy of the source, but it is now generally recognized that the process of unification involves the suppression of complex and significant differences in source character.

In media reports, estimates of magnitude on different scales are often confused with each other, and with estimates of intensity. Vague statements such as 'the earthquake registered x degrees on the Richter scale' should therefore be interpreted with caution.

Summaries of this development are given in the literature.²⁻⁴

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5. Ground-borne vibration — instrumentation and method for data acquisition

J.H. KUEHN, FIOA (B&K Laboratories Ltd, Hounslow)

Instrumentation and techniques available for the measurement of ground vibrations are discussed with emphasis on data acquisition for subsequent processing. Man made vibration is considered, rather than earthquakes.

INTRODUCTION

Measurement of vibration, especially in the field, frequently implies collection of basic data for subsequent processing in the laboratory. This is especially true if complex processing is required.

Direct, on the spot, measurements are usually confined to simple, steady state vibrations.

Ground vibrations can be split into steady, varying and short duration transient. Steady vibrations are likely to be caused by some machinery, varying vibrations are usually caused by various forms of transport e.g. trains and road traffic, short duration transients due to explosive blasting or pile driving.

Vibration can be defined as oscillating motion of a point on a surface. This motion can be defined in terms of direction, magnitude, duration and frequency or frequency spectrum

Taking the simplest form of vibration, that is continuous, simple harmonic motion, - we can express it as:

$$A \sin Wt$$

Where A is peak amplitude

W is angular frequency in radians ($2\pi f$)

This motion can also be expressed in terms of velocity as:

$$AW \cos Wt$$

or in terms of acceleration as:

$$AW^2 \sin Wt$$

Historically, (mainly due to availability of instrumentation at the time) measurements of vibration were frequently quoted in terms of displacement several decades ago, then in velocity terms, while at present there is a tendency to specify acceleration, - although velocity is still widely used.

TRANSDUCERS

Two main types of transducers are now in use, one giving an electrical output directly proportional to velocity and the other directly proportional to acceleration. They are known, quite appropriately, as velocity transducers and accelerometers.

Modern accelerometers utilise the principle of piezoelectricity. In a suitable housing, a piezoelectric ceramic disc is subjected to action of a sprung mass in contact with it. The charge built up due to force acting on the ceramic is directly proportional to acceleration in the principal direction. A variety of designs is used today, including some which use other principles e.g. strain gauges.

Sensitivity of a transducer is quoted in terms of electrical output versus vibration input.

In the case of velocity transducers, this will be given in volts per unit of velocity e.g. Volts per metre per second, or Volts per inch per second.

Accelerometer sensitivity figures are given in V/g (old form) or V/mS^{-2} or in terms of charge output e.g. pC/mS^{-2}

In general, the sensitivity of a transducer is proportional to its physical size.

The dynamic range of a transducer is the range between the lowest clearly measurable signal and the highest signal to which it can be subjected and still give an output free from distortion i.e. in linear proportion to vibration input. The lowest level is normally taken in conjunction with following electronics, which always generate some noise, thus putting a limit on lowest level.

The frequency response describes the behaviour of the transducer when subjected to vibrations over a range of frequencies. Most quality commercial transducers are supplied with a curve showing the frequency response of the individual transducer, or at least showing a "typical" response and perhaps quoting expected tolerances. A typical curve is shown in fig.1.

An important characteristic of a vibration transducer is its directional sensitivity. The principal axis is usually marked or specified, so is the curve showing sensitivity at different angles of excitation.

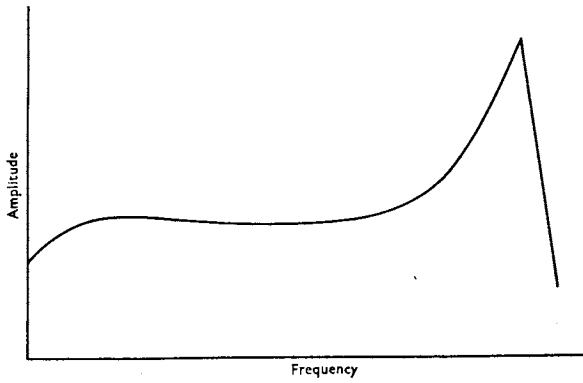


Fig.1. Typical frequency response of a piezo-electric accelerometer

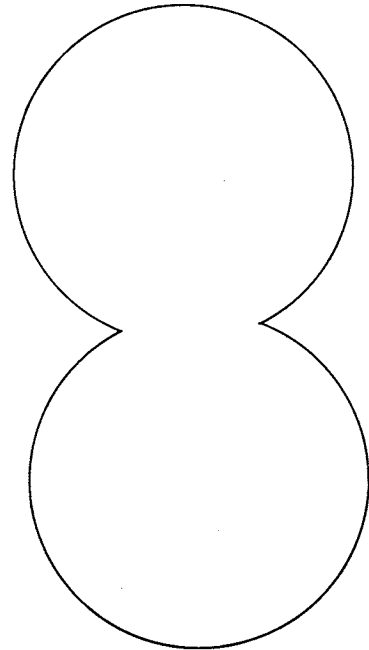


Fig.2. Idealised directional response of a piezo-electric accelerometer

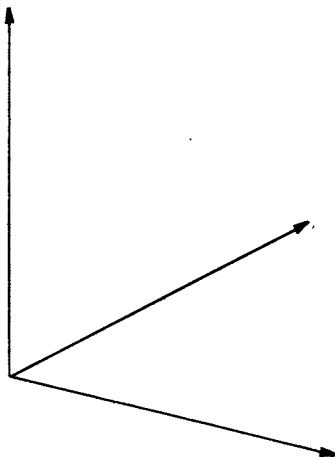


Fig.3. Triaxial accelerometer - principal directions of sensitivity

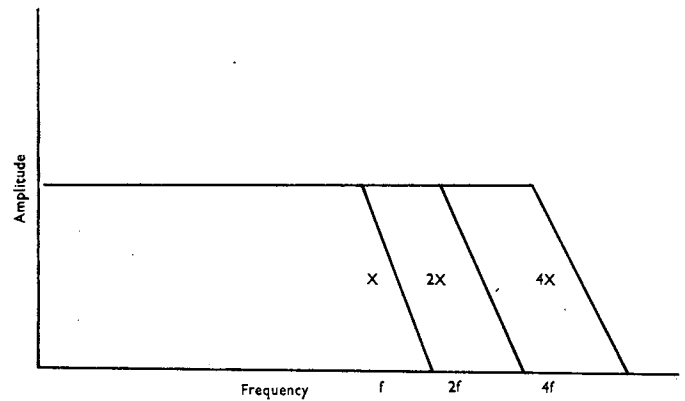


Fig.4. Frequency modulated tape recorder - responses at tape speeds X, 2X and 4X

Minimum transverse sensitivity (90° to principal axis) is often quoted. Fig 2 shows a typical response.

In some transducers, there are limitations to the maximum vibration levels at angles other than the principal.

Behaviour of a transducer over a range of temperatures is also quoted, - which applies to steady state conditions. In recent years, due to discovery of the effect of thermal transients (cooling or heating) on the outputs of transducers, it became customary to quote this figure too.

All transducer performance figures quoted apply to the transducer mounted in the manner recommended by the manufacturer.

The output impedance of a velocity transducer tends to be low, while that of an accelerometer of the piezoelectric type is very high, especially at low frequencies. For this reason, piezoelectric transducers are used with impedance matching preamplifiers, usually charge amplifiers. Charge amplifiers have an advantage over voltage amplifiers in having negligible sensitivity to the length of transducer cable used.

In the measurement of ground vibrations relatively high sensitivity is required, as is linear low frequency performance. High frequency performance is not normally critical.

Occasionally, measurement of vibration in one direction only is required, in which case transducer mounting must be appropriate for such measurements, - the principal transducer sensitivity used must be in line with desired direction of measurement.

When the measurement is aimed at finding the direction of vibration alongside the parameters of magnitude and spectrum, the choice of suitable transducer configuration is important. In such cases, triaxial transducers are used, or 3 transducers located so that their principal axes are perpendicular to one another. If three separate transducers are used, they are usually mounted on one block. Triaxial principle is shown in fig. 3.

As stated before, on-line field measurements tend to be of the simpler kind, when portable indicating or recording devices are capable of providing the required answers.

Such field devices as portable vibration meters are capable of giving recordings of the rms or peak value of acceleration, velocity or displacement, of giving a reading of maximum vibration level reached within a measurement period, or even of providing a record of level against time. Sound level meters may be converted to provide similar facilities, when used with suitable transducers.

Special field instruments have been developed

for the purpose of recording ground vibrations caused by explosive blasting. As these instruments frequently depend upon a waveform recording device, they need activation prior to a blast. To obtain a reasonably readable record, fast chart speeds are essential, - hence the requirement for activation at the proper time.

One rather important question is that of transducer mounting. An iron block, a kilogram or two in weight, can serve as a base on which accelerometers can be mounted either by bolting, cementing or by means of magnetic clamps. A block, possibly with small spikes, ensures that the transducer is well in contact with ground surface.

For vibrations well under the surface of the ground, the transducer may be located in a box. Any connections used should be hermetically sealed, - the seal may be applied externally by means of a suitable compound.

DATA STORAGE

When it comes to multipoint measurements, measurements in different axis for the purpose of obtaining the vector value, measurements aimed at finding exact time histories, spectral information, statistical information, - on-line processing becomes difficult. This is when field data collection for later processing is used.

A tape recorder is the usual device, - providing it meets the basic requirements of dynamic range, frequency linearity over the range of measurements, stability, occasionally phase linearity, availability of the required number of channels.

Instrumentation quality recorders are advisable here, they are the most likely to cover the performance requirements coupled with ease of setting up and calibration. If low frequency data is to be recorded, a frequency modulated type of recorder should be used, - low frequency normally means frequencies below 20 or 30Hz. If accurate waveform information is required, the phase linearity is important, therefore, a frequency modulated recorder again.

FM Tape Recorders offer frequency linearity from DC (zero frequency). The upper frequency limit is a function of tape speed, and type of head used. Most FM recorders provide a range of tape speeds and thus a range of passbands. Typical response given in fig 4.

In a frequency modulated recorder it is possible to record at one speed and replay at another, without losing accuracy.

Most recorders comply with IRIG standard, they use the same ranges of tape speeds, speed ratios (binary) and the same head geometry, making it possible to record on one machine and replay on another. FM recorder's performance is almost totally dependant on consistency and accuracy of tape speed, so tape transport

mechanism and tape must always be clean and in perfect working order.

IRIG standard is based on 1 volt in/1 volt out principle,- where 1 volt means 1 volt rms of a sinewave, or 1.4v peak value. Some tape recorders have the facility for attenuating the input signal to the required recording level, or for providing gain to weaker signals.

Input impedances are not sufficient for direct use with piezoelectric transducers.

The dynamic range of a tape recorder is limited by the maximum level which may be recorded without distortion,- (which in the case of FM recorder is 1.4V) at one end, and by "noise floor" on the other. The ratio of the two values, often quoted as signal to noise ratio, is given in decibels for specified tape speeds, measuring the noise over entire frequency band. Low tape speeds tend to give lower signal to noise ratio Typical figures would be:

3.75 ips	40 - 45dB
7.5 ips	42 - 47dB
15 ips	45 - 50dB
30 ips	47 + dB

The limitation of the signal to noise ratio demands correct signal conditioning prior to recording. Steady signals or signals of known levels are relatively easy to deal with,- but they should always be placed in the "dynamic range window" of a recorder so that peak signal levels are close to the maximum permitted recording level.

Signals of unknown or unpredictable character are more difficult. It is quite easy to end up with data severely distorted by overloading the tape, or with vital data buried in the tape noise. If a multi-track recorder is available, it is possible to use two tracks for the purpose of recording one channel of data. This can be done by using 20dB (a factor of 10) difference in signal conditioning on each of the two tracks or by using channel sensitivity difference of this order, thus increasing the probability of having the data on either of the two channels recorded correctly. There is also a possibility of using an autoranging conditioning system, with data on one track and autoranging code on the other.

There may be occasions when it is desired to

record a small number of short duration phenomena, which may occur sometime within a long period, for example a day. A tape recorder set to continuous recording may require change of tape every hour or two, which means constant attendance, and the possibility of missing vital data while tape changing is taking place.

Special digital data recording devices exist, with transient capture capability,- originally developed for capturing sonic booms. Such devices are set to ignore inputs below a preset trigger level, but to place in memory data following (or even preceding) a trigger. Once the data is captured in the memory, it is immediately and automatically replayed (normally in analogue form) on to a connected and interfaced tape recorder. Following a replay, the system sets itself up for further data capture.

CALIBRATION

Calibration of the entire instrument chain, the transducer, the preamplifier and conditioner and of the tape recorder is always recommended. This can be done by careful checks of individual items of instrumentation prior to undertaking serious tests and measurements, and by pre-setting all the controls.

However, more confidence is gained by calibrating the entire instrument combination immediately before the measurements in the field. In the case of tape recording for further processing, a suitable calibration signal on tape allows the "ranging in" of data processing equipment.

Such a calibration signal may be devised from the transducer subjected to a reference vibration level, or a technique of insert voltage calibration may be employed.

If long cables are to be used in the measurements, they should always be included in the calibration procedure.

With field instruments, special care should be taken over batteries, if they are used. It pays to replace all batteries before major measurement sessions, or at least to ascertain that those used are in first class condition. It is false economy to use the cheapest available batteries. Cold shortens the useful life of a battery considerably.

6. Detection and location of earthquakes and unplanned explosions

C.W.A. BROWITT, PhD (Institute of Geological Sciences, Edinburgh)

An understanding of the principles of seismic source location leads to the development of a seismograph network strategy for detecting seismic waves and determining focal parameters. The value of the macroseismic method is discussed.

INTRODUCTION

1. Seismic methods can be used to detect and locate earthquakes and explosions varying in "size" by ten orders of magnitude, with energy in a bandwidth from about 100 seconds to 100 Hz. In the engineering context it is appropriate to consider the short period part of the spectrum and to recognise that small earthquakes (up to magnitude about 3mb), are unlikely to cause problems to structures. These are, however, important in identifying active sources of seismicity, either natural or man-induced, which could indicate regions of higher hazard.

2. In this paper emphasis is placed on local monitoring requirements, including aspects of instrument deployment and data interpretation. The bias is on the IGS approach and little attempt is made to describe other systems.

3. The more old-fashioned, non-instrumental methods of studying earthquakes still have an important role to play in modern seismology. Macroseismic detection and location is discussed with reference to some recent British events. The strengths and weaknesses of this method (upon which most of our historical data is based) are considered.

INSTRUMENTAL LOCATION OF EARTHQUAKES

4. Before deploying instruments to detect seismic waves and locate their sources, it is important to understand what limitations will be imposed on the interpretation of the data by the geometry of the seismograph network, and by the knowledge of the seismic structure of the lithosphere.

5. An idealised crustal structure is shown in fig. 1, in which layering is discrete and without lateral discontinuities. The P-wave velocity in each layer increases with the depth of the layer. The corresponding S-wave velocity is given, in brackets, assuming Poisson's ratio is 0.25. The possible direct and refracted ray paths of seismic body-waves are shown for a surface focus event (Fig. 1a) and a deeper event (Fig. 1b), together with the travel-time versus

distance plots for the P-wave phases. It can be seen that where a number of possible paths are available (1a), the first arrival at a seismograph station will come from successively deeper layers as the range increases, because the higher horizontal velocities more than compensate for the additional path lengths. The first arrival is usually the one which can be resolved most accurately.

6. Some of the different phases can be seen on the seismogram written by the IGS Lowlands network of stations (LOWNET) in response to the 4.4mb Kintail earthquake of 27 November 1975 (Fig. 2). The range varies from 140 km to 240 km. On channel EGL one can see a small amplitude first arrival which travelled in the high velocity upper mantle material, and a second stronger P phase about 4 seconds later which has followed a crustal path. On channel EAB this latter phase arrives first. S-wave energy (with higher amplitude) can be seen much later on the records although the precise arrival time is not easy to assess in the presence of signal-generated noise. It is difficult to invert the information contained in the seismogram of figure 2 into a crustal structure like figure 1.

7. The most important parameters which can be read from the seismogram are the amplitudes of the phases (enabling the magnitude of the event to be assessed) and their relative onset times, from which the event may be located. Onset times of all phases may be used in the computation of the focus of the event but the higher accuracy in timing the first arrivals makes these most important, and in the absence of other constraints the time differences between first arrivals will give the most accurate location.

8. Figures 3 and 4 illustrate the principles involved in locating an earthquake epicentre (the point on the surface above the focus) from the onset-time differences of first arrivals at a network of stations.

9. In figure 3 labelled asterisks represent

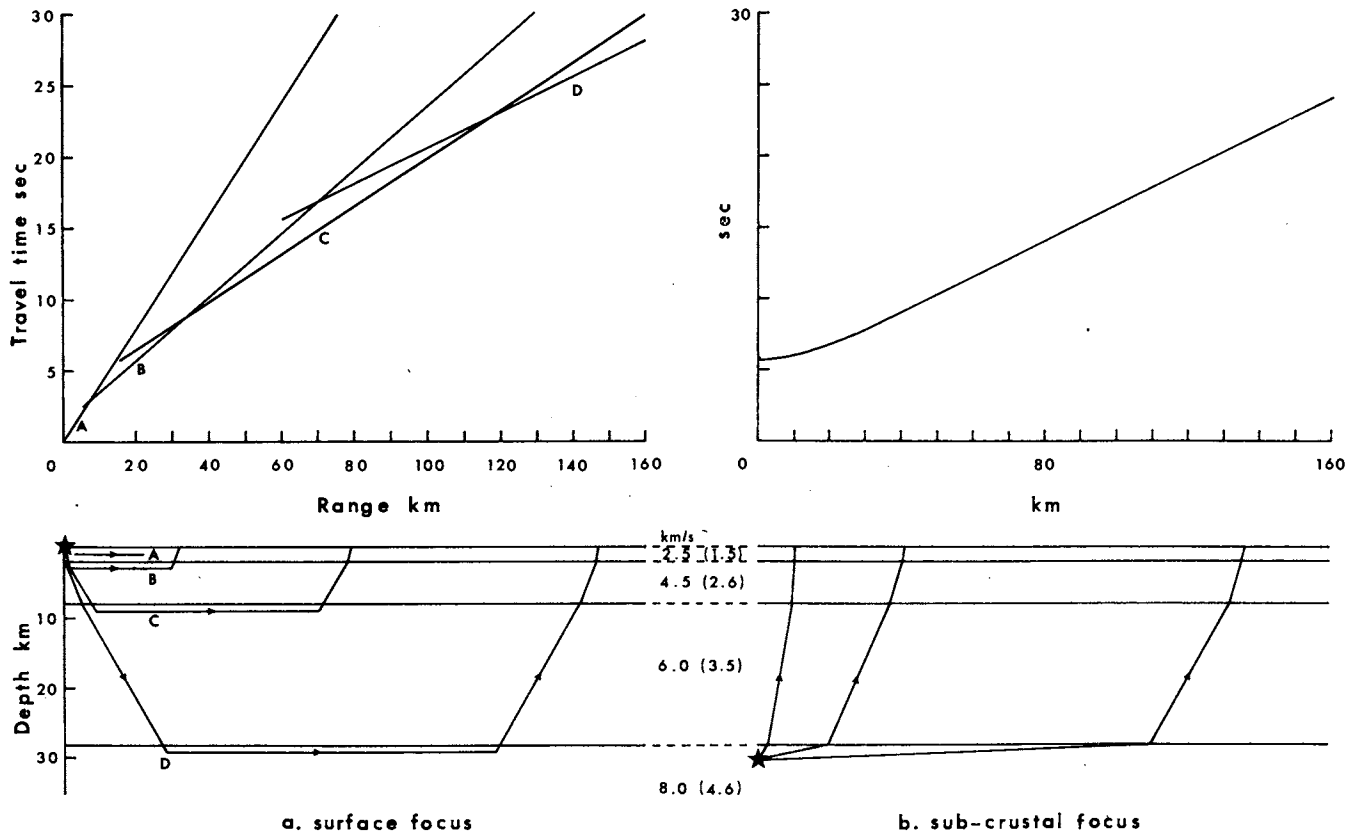


Fig.1. Travel time versus distance curves for refracted seismic waves in an idealised crust

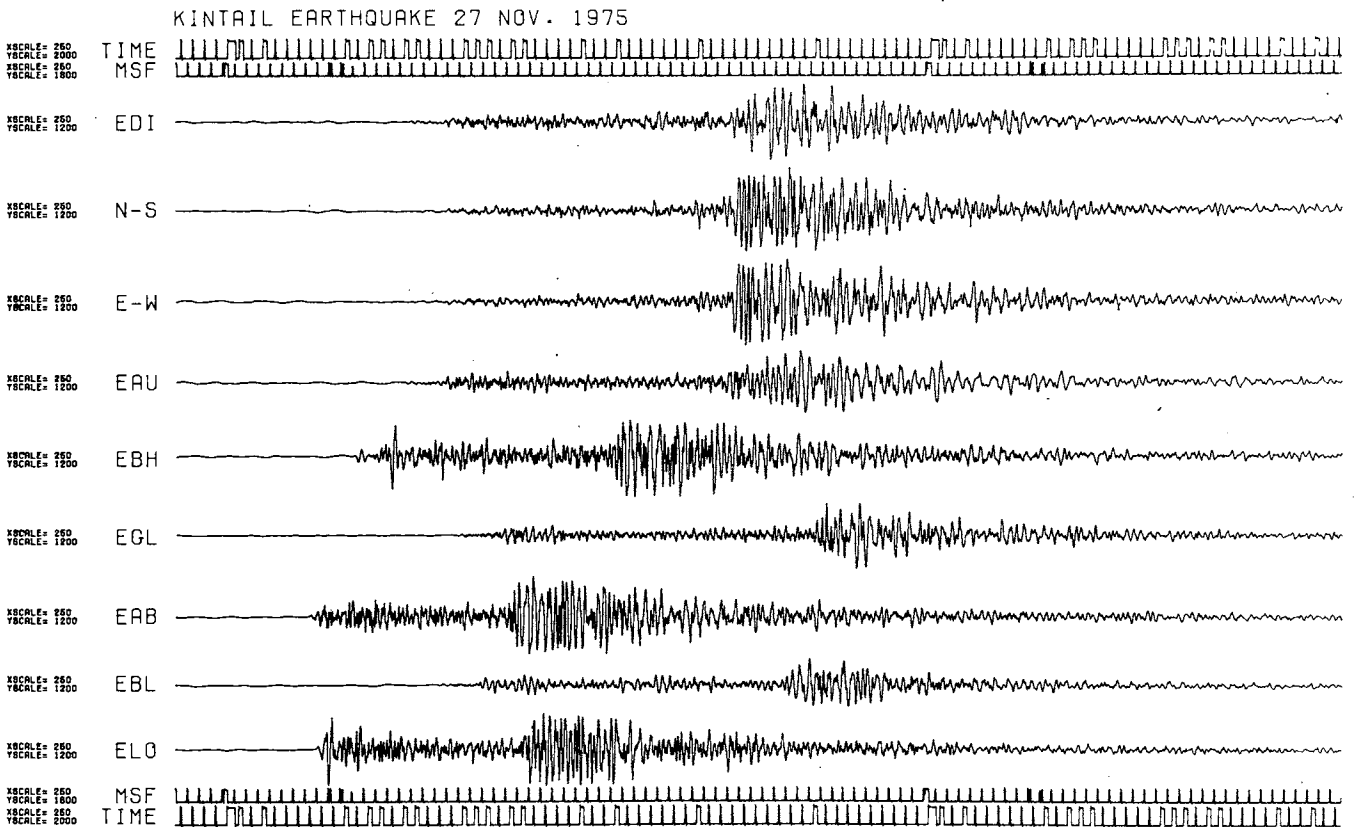


Fig.2. Seismogram of the 4.4 mb Kintail earthquake of 27 November, 1975, written by the IGS Lowlands network of seismograph stations (LOWNET)

two seismograph stations and the lines are loci of constant time difference (annotating numbers are seconds). For a velocity structure with no lateral discontinuities the bisector of the base-line between the two stations is clearly the locus of events which will give a time difference of zero at the two stations.

10. On either side of this line the loci of constant time differences may be computed for a known velocity structure and assumed depth of focus. A suite of charts may be generated for a number of different depths of focus. For a single layer with constant velocity the loci are hyperbolae. The presence of velocity discontinuities, as shown in Figure 1, causes the marked kinks in some of the curves. The positions of these kinks and of the higher order curves are very dependent on the positions of the discontinuities in the assumed structure.

11. In Figure 4 a third seismograph station has been introduced with a second set of curves. For simplicity assume the seismic waves from an event arrive simultaneously at stations AAA and BBB. The epicentre must lie on the zero line for that station-pair. If the arrival at station CCC is also at the same time then the event must lie on the zero locus for the B-C pair. The epicentre is, therefore, at the intersection of the two loci. For an event elsewhere the appropriate intersections will be for non-zero loci. In this case, the use of curves computed for surface focus events on deeper events will result in epicentre location errors which will increase with the order of the curve used. By introducing more stations these will show up as large closure errors which will be reduced when curves computed for the appropriate depth are used. This procedure is essentially one of introducing sufficient equations to solve for the four unknowns x , y , z and T_0 (origin time). This we often do using a computer (ref. 1).

12. Figure 4 illustrates a number of important points:

- i) Epicentres computed with time differences close to zero are independent of depth and structure (if horizontally homogeneous) and are, therefore, very accurate.
- ii) Because of this depth independence an event giving only time differences close to zero does not yield information required to determine its depth from first arrivals alone. This means that for good depth control there must be some stations close to the epicentre and others further away.
- iii) Outside the perimeter of the network the loci of equal time differences become almost parallel. Allowing for uncertainties in the structure and for the observational errors in the relative onset data, equally good solutions can be found anywhere along a fixed azimuth outside the network. Second arrival data (particularly S-waves) can put some constraint on the solution. Without due regard to this problem there is a tendency to accept a solution close to the network whether one is using location charts or computer methods. We have certainly made this mistake on occasions and I suspect at least one important data set elsewhere

in the world is contaminated in this way.

13. Methods have been developed which permit groups of events to be located simultaneously. Accuracy can be improved with sufficient equations being available to solve for uncertainties in travel times and station anomalies, in addition to the prime focal parameters (ref. 2).

INSTRUMENTAL DETECTION OF SEISMIC WAVES

14. At the business-end of any seismograph there has to be some decoupling between the vibration of the ground and the instrument, so that relative motion will take place. This can be amplified and recorded in some way. The pendulum has been the decoupling device since the Chinese used it in the Chang Heng seismoscope 1800 years ago. The modern short period seismometer utilises a spring-mounted magnet as a pendulum, the relative movement of which induces an emf in a coil. This is amplified electronically and recorded on magnetic tape. The signal may then be replayed through filters and various levels of amplification on to paper or into a computer for analysis and interpretation.

15. Where a network of several stations is required there are advantages in telemetering data from remote stations to a central recording facility. It is much easier to obtain high accuracy in relative onset determinations if a single time standard is used, and the logistics of station operation become simpler. Figure 5 is a block diagram of the system we use for network operation. Our permanent network (LOWNET) is based on Edinburgh with radio-telemetered links from remote stations up to 70 km away.

16. The signal bandwidth of interest is between 30 Hz and about 100 seconds period which has normally been covered using a short-period instrument (typically 1 to 30 Hz) and a long period instrument (10 to 100 secs). This arrangement conveniently notches out the high amplitude ambient microseismic noise at about 6 seconds. In recent times wide band systems have been developed which respond to signals in the range 10 Hz to 20 seconds and beyond. These give a more complete picture of the ground vibration but are limited in sensitivity by the microseismic noise level (ref. 3).

17. The 45DB dynamic range of the IGS, Racal-Thermionic short period systems is typical of analogue tape recording instruments. To record the range of magnitudes of interest in local monitoring projects two levels of recording must be used for acceleration levels up to 0.015 g. Events generating larger accelerations can, of course, be detected and located, but for strong motion time series and peak amplitudes we use a triggered accelerograph (the Kinematics SMA-1A) with a full scale deflection for ground accelerations of 50% or 100% gravity.

Network strategy

18. For seismic monitoring purposes there is no simple seismograph package which can be applied to every project. Required station capability, natural and man-made constraints, the level of

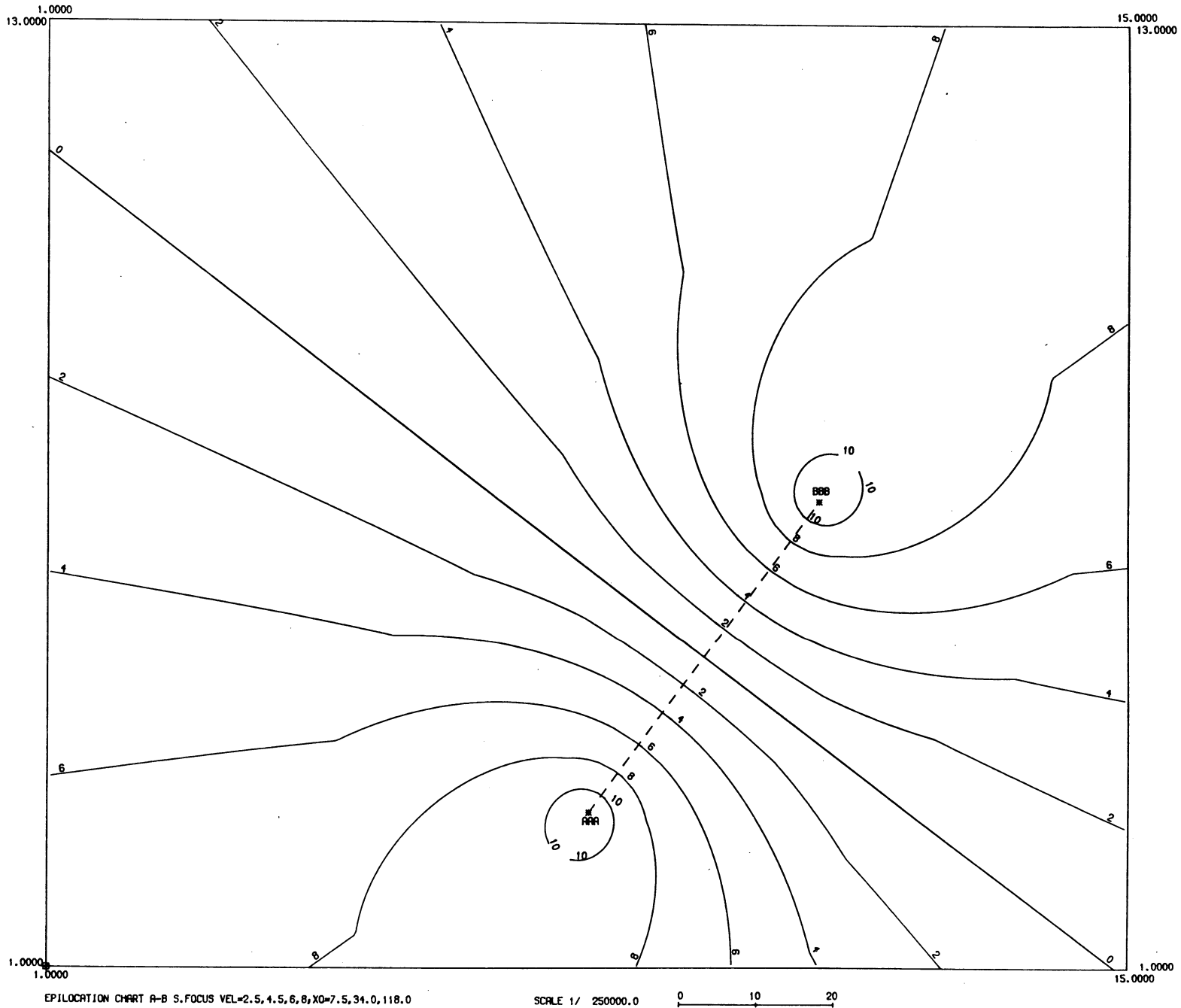
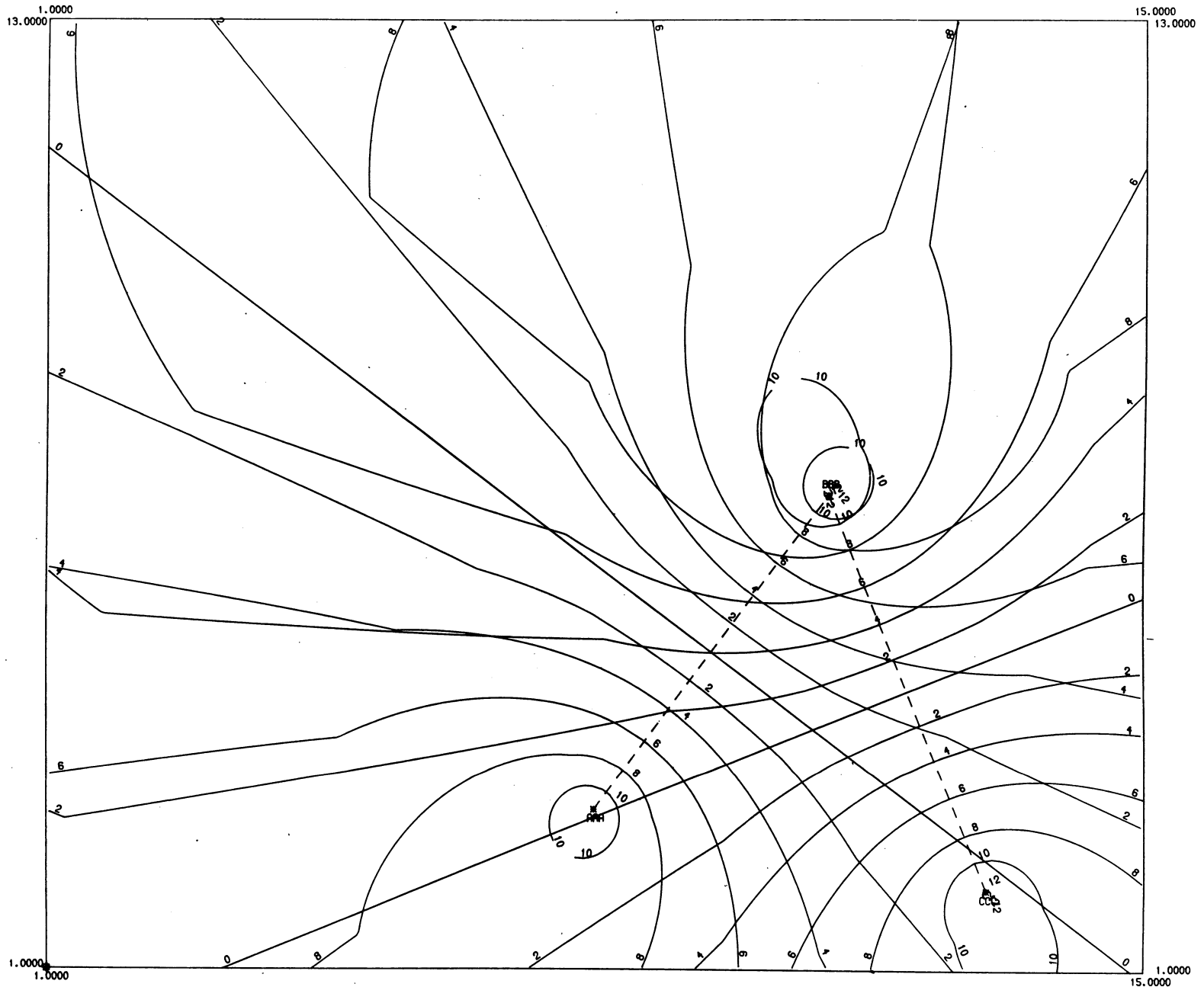


Fig.3. Surface focus epicentre location chart for a pair of seismograph stations



EPILOCATION CHART A-B-C S.FOCUS VEL=2.5,4.5,6,8;X0=7.5,34.0,118.0

SCALE 1/ 250000.0

0 10 20
KM

Fig.4. Surface focus epicentre location chart for two station-pairs

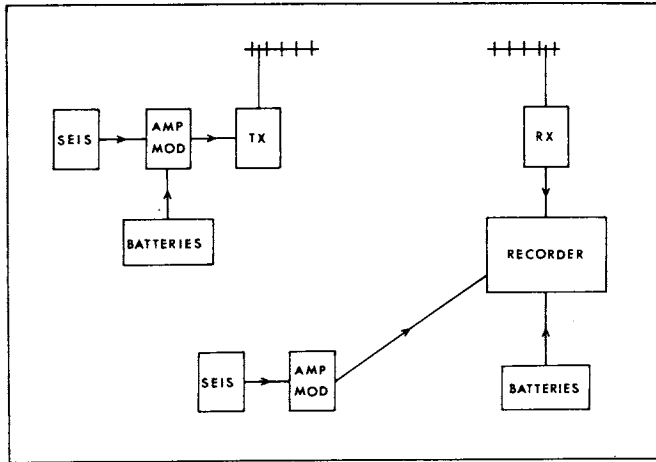


Fig.5. Schematic diagram of seismograph network instrumentation: a number of seismometers and amplifier-modulator units are linked to a central magnetic tape recorder by radio (TX, RX) or by land-line

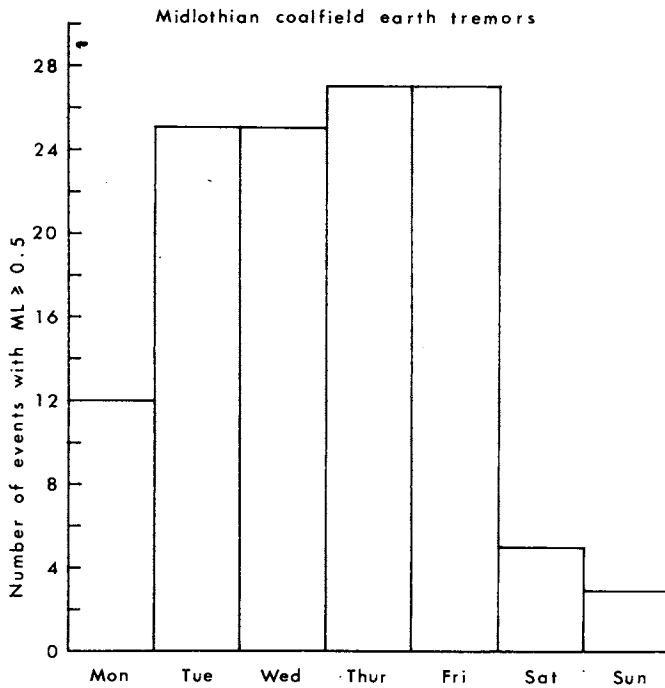


Fig.6. Histogram showing the daily frequency of earth tremors with magnitudes ≥ 0.5 ML in the Loanhead region of the Midlothian coalfield during the period May to December, 1976

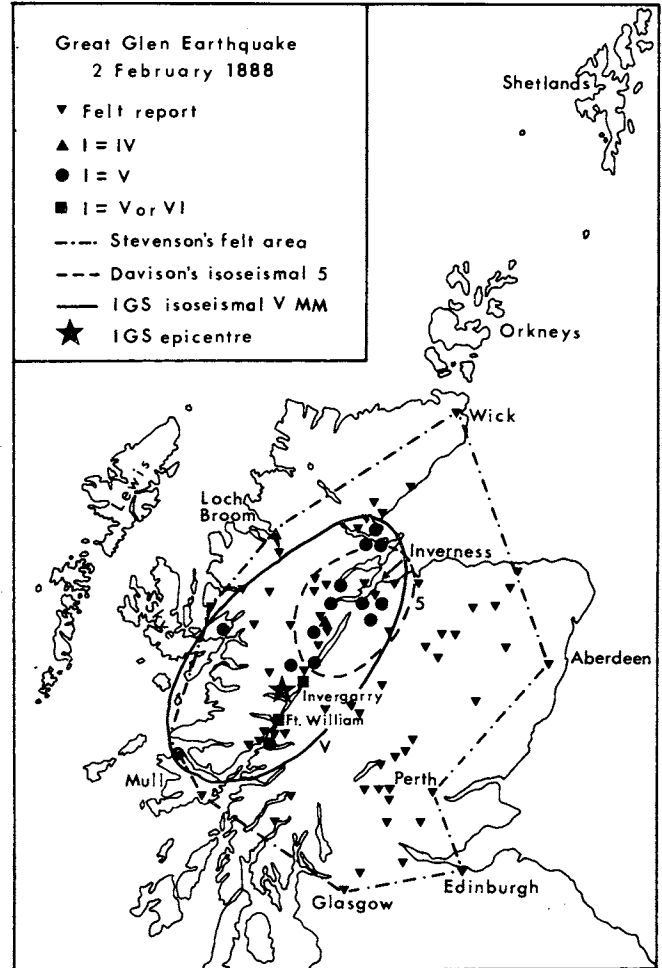


Fig.7. Isoseismal maps of the Great Glen earthquake of 2 February, 1888, after Stevenson (1889), Davison (1924) and Browitt, Burton and Lidster (1976)

on-site support and proximity of regional seismograph stations lead to a wide variation in the optimum monitoring solution for different situations. To arrive at that solution the following questions must be answered:

- 1) What accuracy of event location is required in (a) the epicentre and (b) the depth?
- 2) What is the lowest magnitude event for which high accuracy is required (smallest detectable above background noise or something much larger, possibly only those with damaging potential)?
- 3) What is the extent of the area of interest?
- 4) How much down-time can be tolerated?
- 5) At how many sites is it necessary to ensure that the maximum motion is quantifiable?
- 6) Can existing land-lines be used for telemetering data to a central point and are there any constraints on radio-links (availability of frequencies, terrain, planning permission, security)?
- 7) Will security of remote installations be a problem?
- 8) In what ways might requirements be difficult to meet owing to local noise sources (towns, roads, railways, running water, trees, industrial plant) or inaccessibility of rocky sites, which may mitigate the effects of such sources?
- 9) Are there existing local or regional seismograph stations generating useful data?
- 10) Will there be limited on-site support or is the whole area of interest remote or dangerous (eg potentially eruptive volcano)?
- 11) What level of interpretation is required in 'real time'?
- 12) What is the definition of 'real-time'? That is, what delays in the location of events and determination of peak amplitudes and spectral content would be permissible (seconds, hours, days, weeks or years)?
- 13) Are on-site replay facilities required or is it possible to share those of a remote data-processing laboratory?
- 14) Is there any non-scientific value in the operation (eg educational, political) which may lead to additional requirements?
- 15) Can the cost of the ideal scheme determined by the answers to the above be met?
- 16) What must be sacrificed to bring the cost to a suitable level and is the resulting capability still of value?

19. Answers to questions 1 to 3 will determine the required station density. To improve location accuracy it is recommended that a number of controlled explosions are made to establish travel-times from critical zones in the area, and that experiments be conducted to establish the velocity-depth structure of the region if this has not already been done.

20. Uniform accuracy is not always required over the whole of the region or over the whole of the range of detectable magnitudes. In some situations a simple count of event numbers detected by 2 or 3 stations can give valuable information on the cause of the events. For example, quarries tend to fire consistently at similar times of day, and mining-induced events follow the pattern of daily extraction. Fig-

ure 6 shows the frequency of small earth tremors in the Loanhead area of Midlothian for the period May to December 1976. Many of these were felt locally and they are all in the vicinity of current mine workings. During the 3-week miners' holiday in the summer of 1976 the number of events decreased from several per week to one in the whole period. A similar correlation has been observed at Stoke-on-Trent.

21. A single local station has some capability of discriminating against explosive sources on the basis of the first motion of the shock wave. An explosion gives a compressive first motion whereas an earthquake can give a compression or a dilatation. Because of this it was possible to demonstrate in the early days of the Stoke seismic crisis in 1975, that a locally felt event was not due to blasting. A clear dilatational first motion was observed within a few hours of recording by the first seismograph station.

22. A second class of events which can be recognised on a small number of stations is the "sonic" type. That is, an atmospheric wave which may be felt and heard in a similar manner to an earthquake but which can be easily identified because of its low phase velocity. (At least 10 times less than that of an earthquake). Examples of these are given later.

23. The answers to questions 2 and 5 determine the total number of seismograph channels needed to cover a specified range of vibration levels.

24. Four determines the amount of redundancy to be built in to the system.

25. Eleven and Twelve determine not only the manpower required but also the need for visual monitoring equipment and an on-site data laboratory, possibly including an on-line computer. Interpretation effort will depend partly on the amount of data being collected, and very much on the speed and detail required. This may be a cursory check of a visual monitor to see if a particular distance has been approached or ground amplitude exceeded, with detailed analysis of only the few events meeting pre-set requirements. It could, however, involve an on-line, dedicated computer with appropriate technical and programming support in addition to seismological staff, to provide a rapid, detailed response.

26. The interpretation effort must be increased if it is important to identify the cause of all events observed. For example, in the case of reservoir-induced seismicity, in order to demonstrate any change in earthquake activity it is important to eliminate all explosive sources from the record. These are likely to be more frequent during the development than before construction started. As they are not easily recognised on the seismograms, epicentral regions must be checked soon after the occurrence of events to avoid errors.

27. In question 14 I am suggesting the importance, in some situations, of a local population

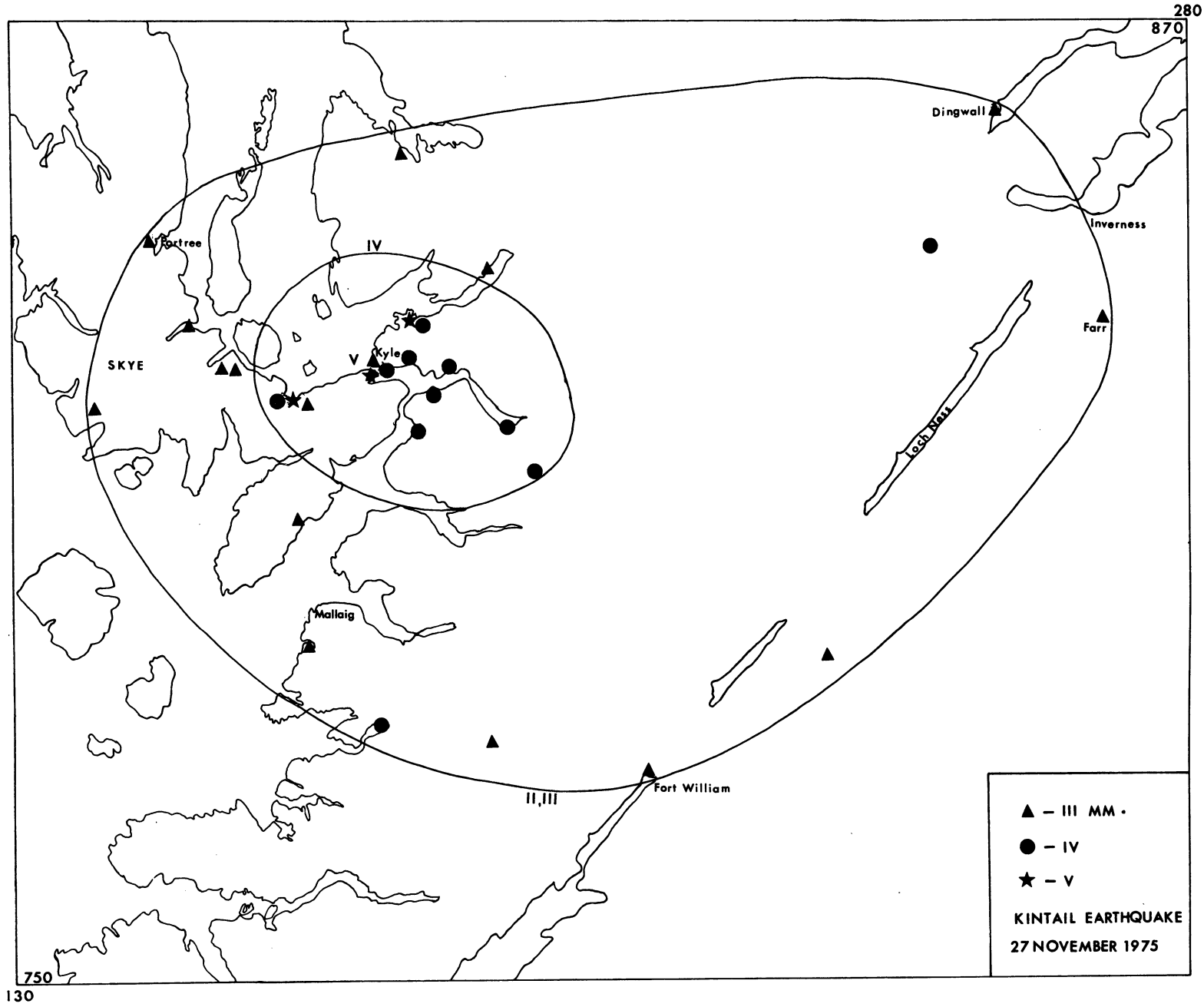


Fig.8. Isoseismal map of the 4.4 mb Kintail earthquake of 27 November, 1975: intensities are given on the Modified Mercalli scale

knowing that objective data is being collected. Such data can in many cases be used to allay the fears which build up in ignorance of the facts.

28. The analysis of requirements will suggest systems varying from a two or three-component station recording on a visual monitor, through a ten-component network recording on magnetic tape, to a multi-channel, multi-recording system with on-line analysis. The former might be appropriate for a site of low seismicity but high sensitivity such as a nuclear waste disposal area. The latter would be appropriate for a sensitive structure in an area of higher seismicity which required automatic shutdown capability, or for nuclear explosion detection purposes.

29. For a regional survey of seismicity the widespread telemetered network concept embodied in the IGS LOWNET configuration around Edinburgh is most appropriate. Accurate hypocentre determinations are obtained within the network and there is a capability of lower precision monitoring of events outside.

DETECTION AND LOCATION USING MACROSEISMIC METHODS

30. It is only in the past 15 years that high density instrumental networks have been yielding near-field observations of earthquake activity. At the present time, the world potential for making such observations is very limited outside California and Japan. In assessing seismic hazard, therefore, we find that we not only must rely on old macroseismic data to extend the time period but that macroseismic studies are still important in supplying data from the many regions which are inadequately instrumented. This is particularly true for areas of relatively low seismicity such as the United Kingdom. The point is well illustrated by the fact that we so often tend to have confidence in our instrumental locations of events if those locations agree with the macroseismic data. Considering the potential capability of modern instrumentation this should, of course, be the other way round.

31. The macroseismic technique involves a study of the effects of ground shaking on people, property and land forms following an earthquake. Although it is a subjective approach, zones of different intensities can be recognised, leading to estimates of epicentral location, felt area, magnitude, depth of focus and attenuation. The last three estimates are usually fairly crude but can be improved if sufficient investigations are made in a particular area, and if some instrumental data can also be obtained.

32. The calibration of macroseismic results by having overlapping instrumental observations is of great importance. A few well-controlled events enable the whole of the historical record, based on macroseismic data, to be interpreted with greater confidence. The long time-span (often in excess of 200 years) is more important to seismic hazard assessment than the relatively short period of instrumental obser-

vation.

33. We have recently been able to conduct a small-scale macroseismic calibration at Stoke-on-Trent. In July, 1975 a damaging event occurred at Stoke for which we obtained one poor quality instrumental record in the far field. Only magnitude could be estimated from this observation. A macroseismic survey yielded information which identified the epicentre and indicated a shallow depth of focus with little knowledge of the uncertainty on the depth. Ten months later a second survey was conducted for a slightly smaller event at the same place. Good instrumental data obtained on this occasion enabled the intensity-depth relationship to be calibrated which, in turn, permitted the depth of the earlier event to be established with confidence. This proved to be the key point in establishing that the damaging event of July 1975 was also mining induced.

34. A third important reason for conducting modern macroseismic surveys (after event location and calibration value) is to gain greater insight into the method - its strengths and, in particular, its weaknesses and the pitfalls.

35. The distribution of questionnaires over a wide area can best be done through advertisements in local newspapers. It is necessary to have some preliminary estimate of the felt region to ensure that newspaper distribution is appropriate. If only part of the region is sampled large errors can occur.

36. In 1976 we recognised a flaw in Charles Davison's excellent work on British earthquakes around the turn of the century: an error which can be attributed to inappropriate regional cover. Figure 7 shows the macroseismic analyses of the 1888 Great Glen earthquake by Stevenson (1889) (ref. 4), Davison (1924) (ref. 5) and Browitt, Burton and Lidster (1976) (ref. 6). Stevenson defined the extensive felt area without attempting to draw the higher intensity isoseismal lines. Davison's analysis led to a determination of his isoseismal 5 (IV Modified Mercalli) surrounding Inverness and giving an epicentre at Inverness. Our examination of contemporary reports 88 years after the event yielded a very different result. It had been felt at intensity V MM over the whole of the Great Glen with isolated instances of minor damage at Invergarry and Fort William. These places were not included within Davison's isoseismal 5. The result is a shift in epicentre of about 50 km, from Inverness to near Invergarry. The explanation of the discrepancy between Davison's analysis and our own is probably that he did not cast his net sufficiently widely, relying on reports from the "Inverness Courier" readers at the north-eastern end of the Glen without realising that in the south-west people read the "Oban Times".

37. A second difficulty in obtaining uniformity of coverage of macroseismic reports is non-uniform population density. This may be illustrated with reference to a recent survey

following the 1975 Kintail earthquake (Fig. 8). The whole area is one of low population. Whilst sufficient data is available from the few towns and villages in the western part of the affected area, elsewhere the isoseismals are poorly defined. The event was clearly felt 80 km to the east of Kyle at Farr and Dingwall but the mountainous area between is one of the most sparsely populated parts of Europe. There is, therefore, no significance in the absence of data points in this area. For the same reason, the northern edge of the felt area is also poorly controlled and the southern boundary is defined by the "road to the isles" (Fort William to Mallaig) which is picked out because of the higher number of potential observers living along the road.

38. The population effect, coupled with poorer communications in historical times, makes us cautious about early event locations. Earthquake reports from sparsely populated areas like the Scottish Highlands may come down to us as single observations. In the absence of other information the epicentre is assigned to the point of observation and the felt area assumed to be small. One can sometimes see the results of this process in historical seismicity maps where strong lines of communication with their higher populations (such as roads and river valleys) are picked out by epicentres. This possibility should be considered before making the assumption that linear features on epicentre maps define simple fault structures.

39. Davison recognised the problem of discriminating between earthquakes and heavy gunfire or bursting meteorites. In modern times, we have the additional problem of sonic boom effects (ref. 7). In some instances these "sonic" events are heard and felt over a wide area and reports are very similar to those following an earthquake. In 1976 two such events occurred in the Edinburgh region. On 16 February an event was felt and heard widely throughout Fife and Midlothian, and on 31 August, 1976 similar reports were obtained from south-east Fife. The high density of seismograph stations in the area enabled us to discount earthquake or ground explosion sources.

40. Without local instrumentation it is sometimes difficult to discriminate even widely felt events. In August, 1976 I collected about 300 macroseismic observations from an area of 11,000 sq km around Midsomer Norton, Avon. The evidence indicates a sonic rather than an earthquake source but it is not definitive. In January 1975 an area of the east Sussex coast experienced a tremor. At the time I had no reason to doubt that this was an earthquake although there were no instrumental records of it. Following our experiences of sonic events in the Edinburgh area, I now have some doubts about the nature of this event.

41. Despite the above difficulties, macroseismic data has improved our knowledge of a number of recent UK events in the absence of good instrumental control. For example, the instrumental data from the Fair Isle earthquake of 9 February, 1973 led to a poorly defined epicentral location nearer to Orkney than Fair Isle. It was felt at an intensity of at least IV MM on Fair Isle but no reports were obtained from the Orkneys. This suggested a more accurate location was several km to the north-east and close to a possible seaward extension of the Great Glen fault (ref. 8).

CONCLUSION

42. One message which comes out of this discussion is that broad-scale monitoring of earthquakes can be most economically achieved using a combination of expensive modern methods (a uniform grid of seismograph stations) and cheap macroseismic techniques from which so much of our existing knowledge has been obtained. However, sites of particular interest must be appropriately instrumented to meet their specific requirements.

ACKNOWLEDGEMENT

43. This work has been supported by the Natural Environment Research Council and is published by permission of the Director of the Institute of Geological Sciences.

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Discussion on Papers 5 and 6

DR BROWITT (Paper 6): Many of the disadvantages of the macroseismic method have been outlined but it clearly has an important part to play in modern seismology. Despite the subjective nature of the method we have found that increasing experience in sifting and interpreting the data has led to greater confidence in the results. This is illustrated in Fig.1 (based on the same data set as Fig.6 of Paper 6) in which the histograms of event frequency against day of the week are shown with the proportion of events reported felt indicated by the double bars. No great effort was made to acquire the felt report data. The information came from about twelve regular reporters in the Loanhead-Polton area and spontaneous communication from local residents. About half of the events were reported felt and the histograms for these show the same pattern as

those based on the instrumental data. A similar situation occurred in the Stoke region prior to the damaging event of 15 July, 1975. Individual residents had claimed that tremors occurred only during the week and never at weekends. The slightly more objective approach of plotting tremor occurrence as indicated by complaints to the National Coal Board in the first six months of 1975 supported the weekday pattern. Subsequently, as Dr Westbrook (Paper 13) has pointed out, our instrumental data proved the point objectively.

These daily frequency plots are diagnostic in determining whether earthquake swarms are caused by mining. Despite the above examples it would be difficult to convince the NCB on macroseismic evidence alone.

The importance of macroseismic data in the

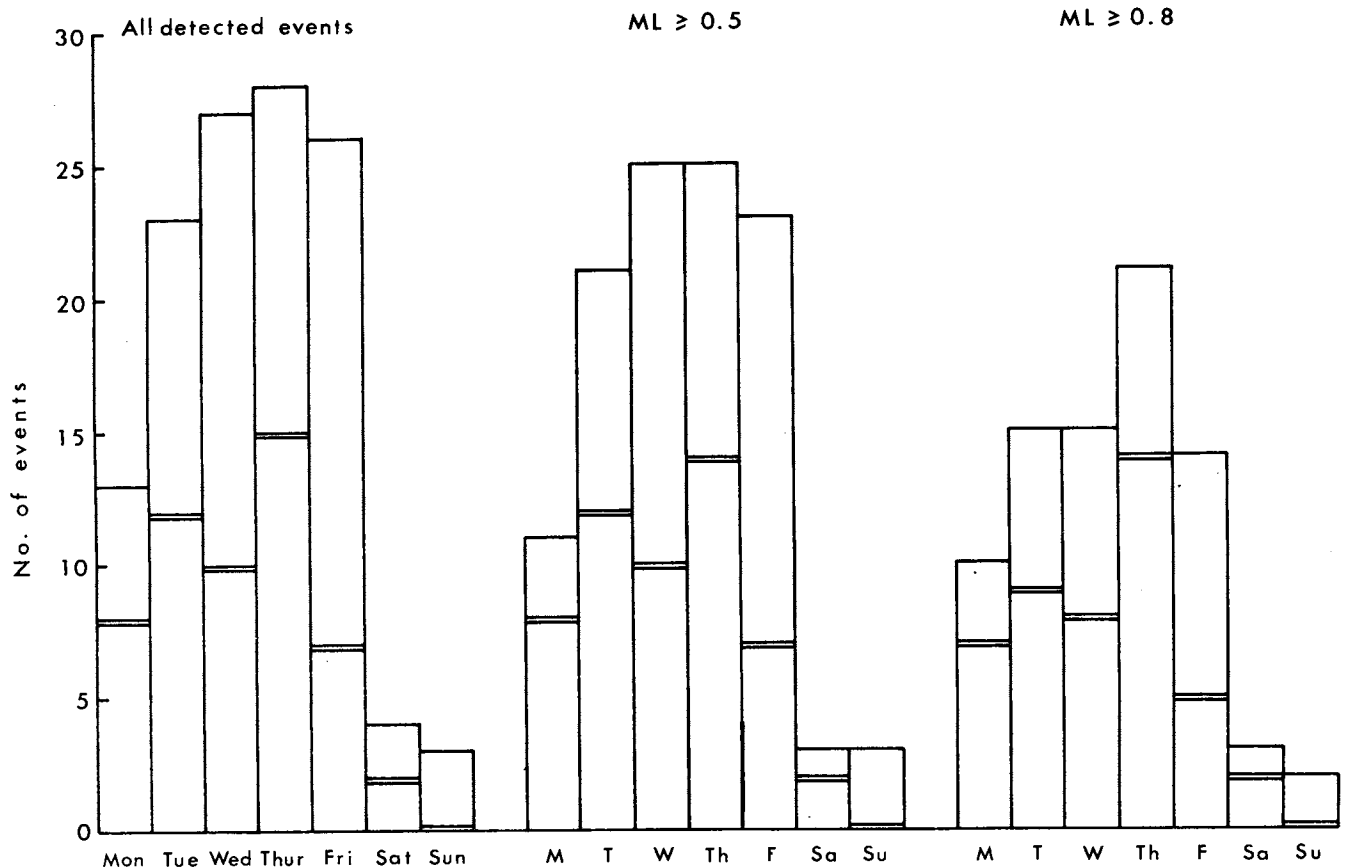


Fig.1. Loanhead-Polton seismic events for the period 21 June to 21 November, 1976. Histograms showing the distribution of event frequency with day of the week. The proportion of felt events is indicated by the double bars. ML is Richter local magnitude

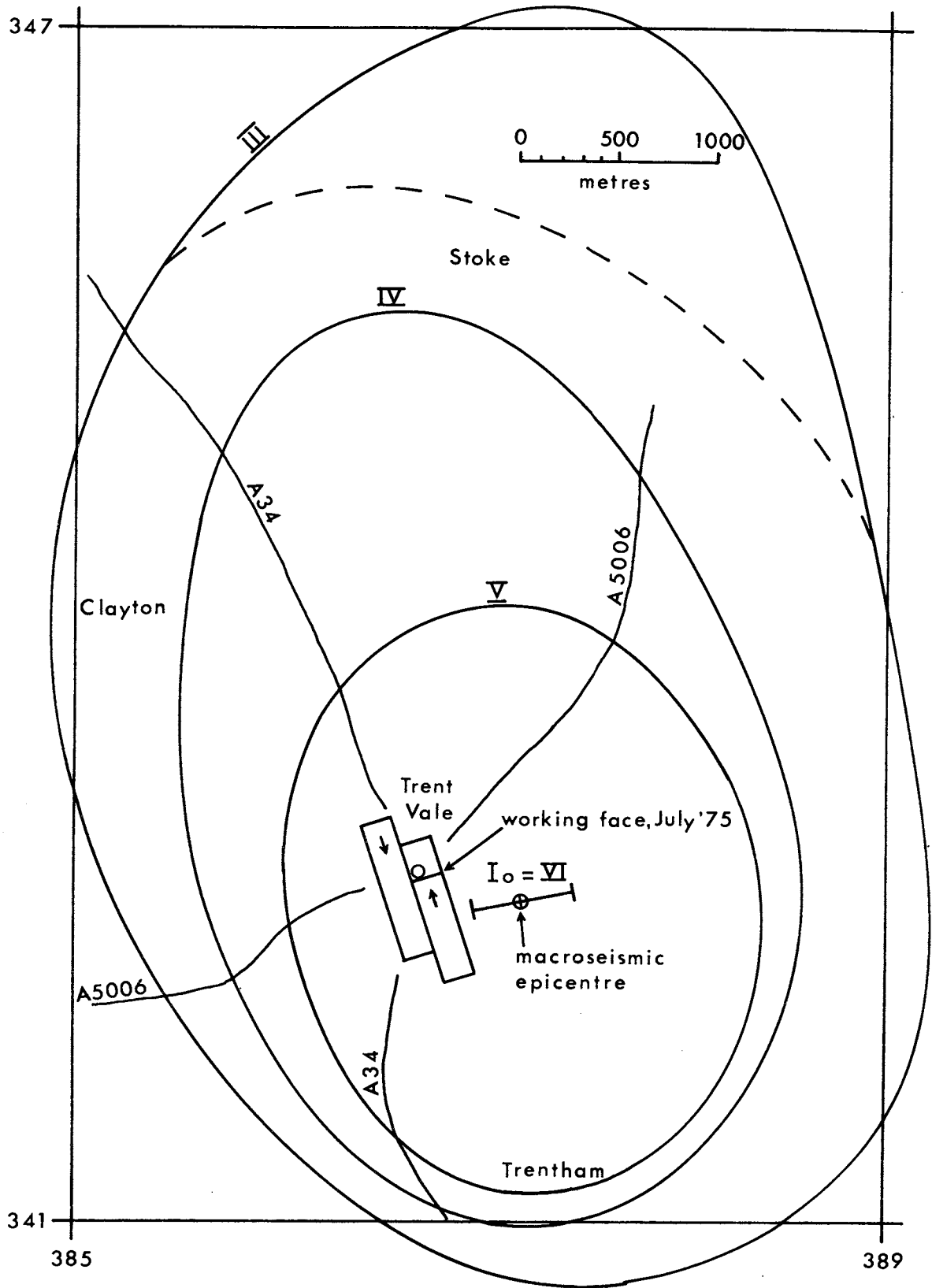


Fig.2. Isoseismal map of the Stoke earth tremor of 15 July, 1975 showing the relationship with contemporaneous mine workings. Intensities are Modified Mercalli

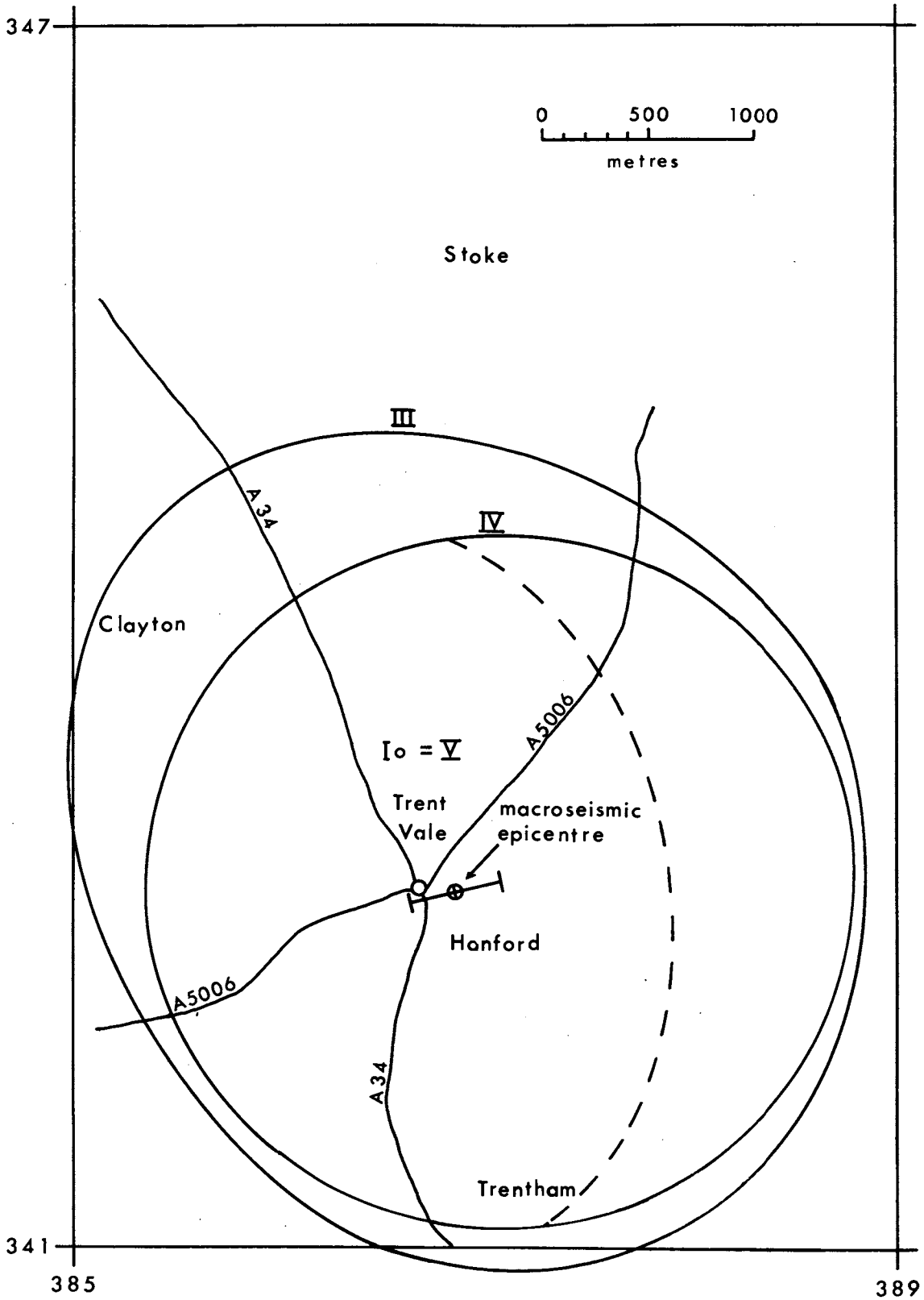


Fig.3. Isoseismal map of the Stoke earth tremor of 13 May, 1976

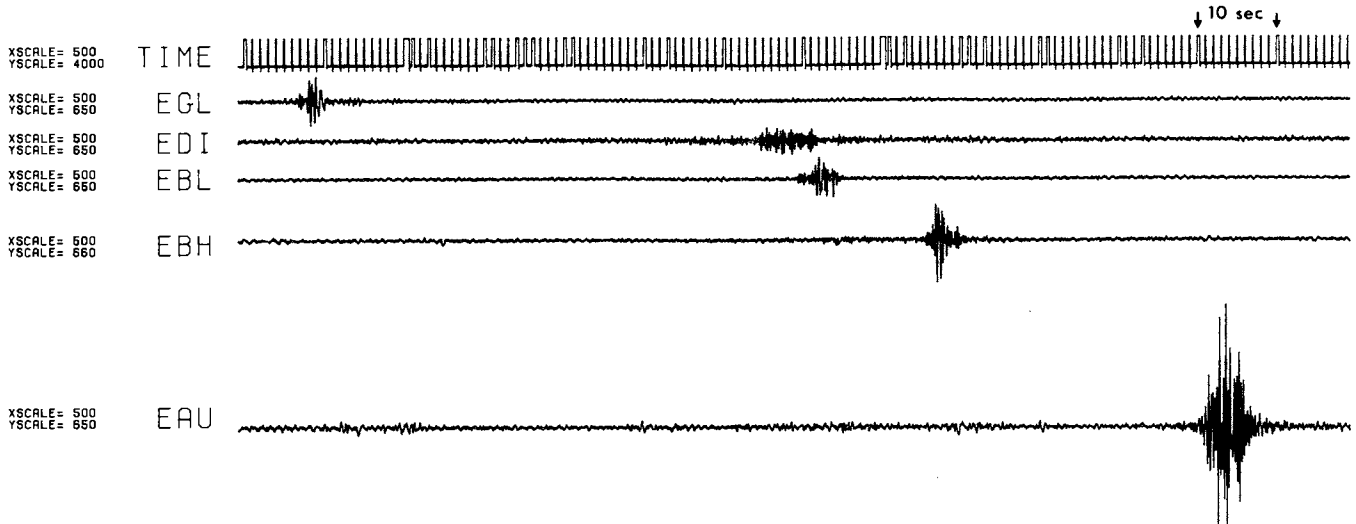


Fig.4. Seismogram of the sonic event of 16 February, 1976 detected by the IGS Lowlands network of seismograph stations (LOWNET)

Stoke investigation has been cited by myself and Dr Westbrook. It is appropriate to illustrate this point. Fig. 2 shows the pattern of isoseismals obtained in relation to the mine workings (at 900 m) and the position of the working face at the time of the event of July 1975. The macroseismic epicentre is within a few hundred metres of the face and the isoseismals show a rapid fall-off of intensity with distance from the maximum of VI Modified Mercalli. This is indicative of a shallow focal depth. Using a number of empirical relations, depth ranges of 0.1-1.0 km were computed with no real knowledge of how applicable the formulae were for this region and the source mechanism.

An opportunity to calibrate the depth relation arose in 1976 during an increase in tremor activity as a second panel (immediately to the west) was worked past the position of the July 1975 coalface. Fig.3 shows the isoseismal map generated for one of the larger events in this swarm. The macroseismic epicentre is close to that determined instrumentally and to that of the 1975 event, giving greater confidence in the latter determination. We assume an intensity-distance relation of the Blake-Shebalin form:¹

$$I_0 - I_n = C \log (D_n/h)$$

where I_0 is the maximum intensity and I_n the intensity of the nth isoseismal, at distance D_n from the hypocentre at depth h . The relation may be calibrated for C in the analysis shown in Tables 1 and 2.

Dr Westbrook determined the depth of the 1976 event (Table 1) as 750 m from instrumental data. Fitting this depth with the macroseismic data we obtain $C = 4.5$ and $C = 2.4$ for $I_0 - I_n$ equal to 1 and 2 respectively. Table 2 shows the results for the 1975 event using these C values appropriately. The depth of focus obtained is internally consistent at 600-700 m. This analysis establishes a close spatial relationship between the damaging 1975 event and that of 1976. The 1975 event was followed by a swarm of activity which was mining-induced (established with instrumental data) and the 1976 event was part of a similar swarm. There can be little doubt that

the 1975 event was part of the same sequence and that it also was caused by mining.

By permitting the values of C to be determined, the macroseismic analysis coupled with the instrumental hypocentre has established an attenuation law for the area relating intensity differentials to hypocentral distance. The agreement between the depths for $C = 4.5$ and $I_0 - I_n$ equal to 2 and 3 for the 1975 event indicates some linearity of scaling beyond isoseismal IV.

Finally, it is appropriate to illustrate the obvious difference between a 'sonic' event, involving the coupling of a slow atmospheric wave with the ground in the immediate locality of a seismometer, and a genuine earthquake from which fast seismic waves propagate. Fig.4 shows the seismogram of the sonic event of 16 February, 1976 written by the IGS Lowlands network. The

Table 1. Event of 07.16, 13.5.76, $I_0 = V$

I_n	$I_0 - I_n$	x_n , km	h , km	
			$C = 4.5$	$C = 2.4$
IV	[1]	1.7	1.3	[0.8]
IV	1	1.5	1.0	-
III	[2]	2.0	[0.8]	-

Table 2. Event of 19.50, 15.7.75, $I_0 = VI$

I_n	$I_0 - I_n$	x_n , km	h , km	
			$C = 4.5$	$C = 2.4$
V	[1]	1.4	1.0	[0.6]
V	[1]	1.6	1.2	[0.7]
IV	[2]	1.9	[0.7]	0.3
III	3	2.5	0.6	0.1

distance between the extreme stations (EGL and EAU) along the apparent azimuth of the signal is 45 km, giving a phase velocity of 0.39 km/s. By comparison, even the relatively slow S-wave energy from the Kintail earthquake (Fig.2 of Paper 6) swept across the network with a velocity of about ten times this value. Fig.4 shows an apparent anomaly in the amplitudes of the signals with the furthest station giving the greatest particle velocity. The coupling between an atmospheric wave and the ground is highly dependent on the local soil conditions and this is presumably the explanation of the anomaly. As an aircraft was not observed, the alternative possibility of the flight path being closer to EAU seems unlikely.

DR P. SRINIVASULU (Structural Engineering Research Centre, Madras, India): I have noted that B&K is marketing a wide range of piezo-electric accelerometers for different applications. During the discussion on Papers 1-4, a number of delegates expressed the view that particle velocity is a more appropriate parameter for vibration measurement, especially in the frequency range 2-100 Hz. Viewed from this angle and considering the difficulties of field calibration of piezo-electric transducers, and the problem of their high impedance which necessitates use of special charge amplifiers with such transducers, is there any special reason for B&K to choose the piezo-electric principle for their transducer development?

Would Mr Kuehn substantiate the statement that the sensitivity of a transducer is proportional to its physical size? Perhaps he has in mind the piezo-electric accelerometers, and the physical size refers to the size of the mass resting on the crystal.

MR KUEHN (Paper 5): B&K transducers are intended to have performance characteristics which make them fairly universal. They have sensitivities and frequency responses which make them equally useful for ground vibration measurement and machine vibration measurement, with a total frequency range of 1 Hz or less, up to some 10 kHz. The piezo-electric principle used in the B&K designs gives very good, all round performance. Strain gauge accelerometers on the other hand are useful only at the very low frequency end and velocity transducers have both low frequency and high frequency limitations. Velocity transducers with which I am familiar do not possess low frequency performance required for ground vibration work, in which, as you say, the main frequency range is 2-100 Hz.

I agree that with piezo-electric accelerometers you require charge amplifiers or high impedance voltage amplifiers, but these are easily available. They are equipped with very useful features: quite often they incorporate integrating filters, so that acceleration or velocity can be measured or recorded. You mentioned difficulties of field calibration of accelerometers. No calibration device known to me covers all the parameters, but B&K do make a battery-operated, field accelerometer calibrator type 4291. It can be used with most B&K accelerometers and others which use the same method of fixing, or which

can be adapted to 1032 NF. This calibrator operates at 1g and at 79 Hz, which is equal to a frequency of 500 rad/s, which facilitates fairly easy calculations of velocity figures as required.

Modern accelerometers, from leading manufacturers like B&K and Endevco, according to many tests I have carried out, retain their sensitivity over many years within a few per cent: I could quote figures of 10-15% over five years. This applies to accelerometers which have not suffered mechanical damage due to being dropped on stone or concrete, due to hammer blows etc. Cables, unless well treated, can give problems of intermittent or poor continuity.

My statement regarding size and sensitivity was of a general nature, and I was discussing piezo-electric accelerometers at the time. If you look at any manufacturer's catalogue, you will see that larger size is normally associated with greater sensitivity. In accelerometers, a large mass acting on the piezoceramic will normally mean higher output for the same acceleration.

MR R.G.T. LANE (Sir Alexander Gibb and Partners, Reading): Dr Browitt refers to the difficulty of fixing the plan position of an event using three stations - as shown by the parallelism and near-coincidence of the lines of equal differential arrival time. The difficulty can usually be resolved by checking against the distance calculated from the arrival time difference for P and S waves.

DR BROWITT: In the extreme example given (where, from first-onset readings only, the mislocation was ± 25 km along a fixed azimuth) the solution would normally be better constrained if the S wave onset were used. However, S waves often do not record well or can easily be misread from the record. The depth of the event would also affect the interpretation of epicentral range using S-P separation, and, outside the network, depth can be traded off against origin time over a wide range of solutions. There would remain the difficulty of assigning the earthquake activity to a particular fault in an environment where there were many faults.

MR R.G. REBBECK (British Rail, Derby): Standards deal with sinusoids. Real man-made vibrations are more often non-stationary and random. Before we talk of signal analysis we want to know what parameters are needed to describe the damaging effect to structures and the perceptibility for a person (which may well be quite different things) of a random signal.

Is it just peak amplitude or velocity or acceleration? - in which case we don't need a very sophisticated analysis. Or is it something else? - in which case, what?

MR KUEHN: My paper was concerned with basic data collection, for subsequent analysis and processing. 'Peak particle velocity' was mentioned by a number of speakers, simply because in vibrations caused by explosive blasting it has become customary to quote this value when looking at possible damaging effects on buildings. Most literature available on the subject seems to be in agreement on this point.

With vibrations of a different nature, perhaps other parameters should be considered; civil engineers should be the right people to answer this. I believe that some form of statistical analysis may give useful information here. When it comes to human perceptibility, different criteria apply; Papers 15 and 16 deal with this subject.

DR P.L. WILLMORE (Institute of Geological Sciences, Edinburgh): The whole time history of disturbance, including the Fourier spectrum of the main shock and its aftershocks, is important, for if some resonance of the structure is sufficiently severe to initiate cracking, damage can spread through the structure as long as shaking continues.

MR D.B. O'NEILL (Crockett and Associate, Carshalton): What are the difficulties associated with the accurate integration of accelerometer output to yield accurate velocity or displacement signals from transient vibrations?

MR KUEHN: I must refer to my discussion of pass-band necessary to measure accurately an acceleration signal, which is not a steady sinusoid. I

pointed out that a short-duration transient (even though to the eye viewing an oscilloscope it may look like a sinusoid, but having finite beginning and ending) is a broadband signal in the frequency domain. In order to record correctly, the instrumentation system must have linear amplitude and phase response over the required part of the spectrum. If this signal is to be correctly integrated, the integration must cover correctly the part of the spectrum mentioned before.

If you use a B&K sound level meter for vibration measurement, acceleration signals are dealt with correctly down to about 2 Hz, but if you use the little integrator, then the low frequency end is not so well covered. Specifications for ZR.0200 clearly show a low frequency limit of 10-25 Hz, depending on the sound level meter with which it is used, and phase response near the low end is not perfect.

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7. Ground-borne vibration— instrumentation and methods for data processing

A.P. MILES (Wolfson Unit for Noise and Vibration Control, Institute of Sound and Vibration Research, University of Southampton)

Our modern world, full of technological innovations and massive construction projects sets the scene for many problems associated with the propagation of vibration through the ground. The simple equipment, which was used only a few years ago, has rapidly become obsolete and simple analysis of vibration amplitude and frequency no longer serves to answer all the problems encountered. The advent of the integrated circuit has solved many electronic problems and the most complex equipment of yesterday can, today, be packaged into rugged portable analysers for direct field use. A review of three trends in instrumentation is given in this paper, with particular emphasis on the adaptive use of equipment from other technologies.

INTRODUCTION

1. The broad front of ground borne vibration covers many fields of geology and seismology and includes every day problems of traffic and construction engineering. The requirements for various types of analysers are formidable, for instance, in seismology the amplitude and arrival times are important; in construction engineering the impedance of the soil and to most of us living in cities the statistical incidence of annoyance created by heavy road traffic.

2. These various requirements can be split roughly into two categories: amplitude analysis and frequency analysis. The field of electronics has expanded and increases in knowledge with frightening rapidity. Equipment which was the most up to date two years ago is often completely obsolete within half of its life time. The engineer and scientist working in any field where problems are solved by complex electronic machines must therefore face the uncertainty of this obsolescence problem.

3. This paper will review developments in instrumentation in the field of ground-borne vibration analysis, and in particular look at allied technologies in an attempt to suggest and predict current trends in the field of signal processing.

AMPLITUDE ANALYSIS

4. Historically the amplitude analysis of vibration signals has been fairly uncomplicated although, often as not it has required considerable skill on behalf of the operator in interpreting the results. The most generally used instruments in the field have been direct writing pen recorders and ultra-violet light galvanometers. These instruments are still widely used and have been much improved since the early days. They have recently been complimented by direct reading energy meters and statistical analysers, and by more versatile fibre-optic and digital transient capture devices. Tape-recording of course, has

been with us for some time and can considerably enhance the usefulness of many of these systems.

Direct Writing Pen Recorders

5. Direct writing recorders have been in existence for very many years, and will be familiar to everyone. Major disadvantages have been in the pen writing system and the frequency response of the indicating mechanism. Integrated circuit operational amplifiers and advanced designs of stepping and servo motors have enhanced the performance of the latter, having increased the frequency response to between 400 - 600 Hz.

6. Pen systems too, have been improved and jet pen writing systems are common, although at high pen speeds the operator can still expect to be spattered with ink. Multi-pen recorders with up to 10 channels are also available, although higher frequency response is only obtained with single channel systems.

7. Pen recorders produce clearly reproducible traces with multichannel capability at relatively low cost. These recorders are particularly suitable in seismology where low frequencies are encountered and where the relative arrival times of each trace can be clearly defined. Because of the low frequencies involved in this work, tape recorders replaying the data at 4 to 16 times original speed are often employed, to reduce the total analysis time.

UV Recorders

8. Ultra-violet light recorders have been extensively employed in the vibration measuring field. They use high sensitivity galvanometers which deflect a light spot from an ultra-violet source onto sensitive photographic paper. Because of the high sensitivity they can be used directly at the output of many seismic transducers, without any signal amplifier, making them suitable for field operations where suitable electricity supplies are available.

9. Early UV recorders suffered from fogging of the traces when exposed to light and it was often difficult to identify individual traces. Modern recorders, use much improved photographic emulsions and are less sensitive to daylight. Positive identification of traces is available on most recent models, which may have as many as 48 channels with built in pre-amplifiers and battery operation facilities.

Portable Vibration Meters

10. Major advances have been made in the portable vibration meter field, mainly as a result of the demands made by mechanical engineers, and meters are offered by many manufacturers. They are normally single channel instruments with direct reading meters, and an accelerometer as the transducer. Most instruments have sufficient sensitivity to permit observation of traffic excited vibration on building foundations and other structural elements. The meters read in R.M.S. or peak units which may be displacement, velocity or acceleration, and one or two are intrinsically safe for use in mines and petrochemical plants. These meters are simple to operate and provide outputs for tape recorders and portable chart recorders.

Graphic Level Recorders

11. Graphic level recorders are rather like chart pen recorders but contain precision rectifiers and log amplifiers to give a presentation of level against time. Battery operation is still available on at least one of those recorders and it may be used for automatic frequency analysis with suitable filters.

Transient Recorders

12. Transient data has long been a problem and up to very recent years an ideal solution to the analysis of impulses has been impossible. For instance, the exact timing of many transient events is unknown before the event, and portable recorders have been unable either to cope with the range of frequencies or to trigger successfully at the onset of the signal, without some loss of data. Consequently UV recorders had to be left running with severe loss of paper before the event, and tape recording was usually cumbersome and time consuming.

13. Advances in the medical field have produced instruments capable of handling these problems. Surgeons and medical workers have long been aware of the problems of recording heart failures and cerebral disturbances which, like seismic data, occur predictably but with a degree of chronological uncertainty. Developments in the uses of fibre optics and in digital circuitry have gone a long way to solving these medical problems and most of this equipment is suitable in the vibration measuring field.

14. The fibre optic technique uses a conventional oscilloscope coupled by fibre optic light pipes to a roll of light-sensitive paper. The paper may be moved continuously, or stepped, and the basic oscilloscope contains standard pre-amplifiers for up to four channels of transducers. Once the trigger threshold has been set, the

system remains in standby until an event, when the scope triggers and writes onto the paper. On completion of the trace the paper steps to the next frame and the scope reverts to standby in readiness for the next event.

15. Transient recorders with digital memories have become increasingly available from several sources. These recorders again have up to a four channel capability, with built in monitoring oscilloscopes, and full computer compatibility. The kernel of these devices is a recycling digital memory, which when triggered stores the whole of the transient plus some of the time before the event occurred. This stored data can be outputted onto paper tape punches, for later computer analysis, or onto digital or analogue plotters and chart recorders at speeds to suit the device in use.

16. Additional features of these devices include the ability to perform mathematical operations on the stored data and if necessary to output this information down telephone lines to remote terminals.

Spin-Off Technology

17. Advances in the field of acoustics often have considerable applications in vibration analysis by virtue of the similarity of the data. To cite two examples of this spin off, current British legislation calls for the analysis of industrial noise on an equivalent energy basis, and for the analysis of community noise on a statistical basis. Direct reading instruments have been developed to analyse both these parameters and they are briefly described below.

18. Firstly the assessment of noise on an equal energy basis where the intermittent noise level is equated in terms of a sound level which has equal energy over the same time period. Bearing in mind the need to attempt to quantify damage to buildings as a result of many intermittent vibratory processes this type of measurement may find increasing popularity as the damage mechanisms become better understood. The instruments themselves accept inputs from microphones and from accelerometers. Once the transducer has been connected the instrument is switched on and integrates any information which occurs during the time it is operating. The displayed output is the integral under the acceleration vs time graph, and this result may be displayed over a period up to several days with printer outputs at hourly intervals if desired.

19. The second type of instrument (Fig.1) measures the probability of a specified noise being exceeded during the measuring period. Again these instruments may be connected to vibration transducers, and the data analysed over periods up to 10 days. Thermal printers are often incorporated and print outs at pre-determined time periods are available. These instruments find particular use in the assessment of time varying signals where periods of intense activity may be interspersed by inactive periods.

20. As an example the effects of wind on church spires have been quantified in this way, without the use of complex tape recorders or UV recorders on site, and the analysis has been completed without an additional replay stage. Similarly the energy input to a building foundation as a result of pile driving was easily arrived at using the former system.

Mini Computers

21. Probably one of the most significant developments in latter years has been the introduction of mini-computers (Fig. 2). These digitally based devices have very considerable arithmetic capabilities and a whole range of peripheral devices permits large storage capacity and the ability to talk in plain language to these systems.

22. In terms of analysing amplitude information from vibration transducers they have tremendous power. Large arrays of transducers can be set-up and the signals converted to digital coded signals for direct connection to multiplexer units and post office data transmission lines. The receiving mini-computer can perform a whole range of functions from determining the level and standard deviation of each signal to signal averaging and determination of source location and reflecting planes by direct manipulation of the arrival information and signal phase.

FREQUENCY ANALYSIS

23. The instrumentation previously discussed is primarily concerned with the measurement of amplitude information. With the exception of the latter specialised analysers, some frequency information is normally available even if only in the form of a simple "eye-ball" of the trace on an oscilloscope. The visual observation method falls down where the signal is random and complex or transient.

24. The concepts of filtering are well known, and in the simple case a rectangular window is slotted into the frequency domain which admits frequencies only within the passband of this slot. Filters of this type are many and various and most of the direct reading portable vibration meters mentioned earlier incorporate such a device. Unfortunately most problems associated with ground-borne vibration are at low frequencies (below 1000 Hz) and with non-stationary signals considerable error may be introduced in the determination of the filter output by inadequate averaging in the level detector. Small vibration meters often suffer from this problem, and many users of equipment seem oblivious to this fundamental source of error.

25. The frequency analysis of impacts and shocks is a more complicated problem and because of the increased use of piling in modern construction is taking on a more significant role in everyday vibration work.

26. For instance many factories assembling the minute parts of integrated circuits used extensively in the equipment under discussion, experience problems from construction sites close

by, or from transportation vibration. In many of these instances the only solution lies in correct isolation of the factory floor. Implicit in this sort of problem is some knowledge of the excitation frequency, and simple analogue filters are unsatisfactory because of their slowness or their inability to handle the transients without distortion.

27. Integrated circuits have brought forward a range of sophisticated analysers meeting these demands. These types of equipment are often termed "Real Time Analysers" as they operate on the input signals with exceptional speed so as to complete the analysis in almost real time. Three types are available at the present time; the parallel filter analyser, the time compression analyser, and the truly digital filtered analyser.

Parallel Filter RTA

28. The parallel filter analyser is most frequently found using one-third octave constant percentage filters with frequency ranges from 2 Hz to 40kHz. Each filter has associated with it an R.M.S. detector and averaging circuit. The averaging time of each filter is selected to give a constant known error for non-stationary signals, and the output of each detector is scanned by a multiplexer and each sample value stored. Associated with the multiplexer is a logic array which outputs the data onto a display oscilloscope or X-Y plotter. The advantage of this arrangement over sequential scanning filters is that a variable averaging time is applied to each filter and the multiplexing can be controlled to complete the analysis in the shortest possible time, with excellent statistical confidence.

29. At low frequencies, however, the correct result is only obtained if there is sufficient data to occupy at least one averaging period, and for some transient work this may not be the case.

Time Compression Analyser

30. The time compression analyser operates quite differently from the parallel filter concept described above. Filtering is normally achieved by one fixed bandwidth filter with a non-varying centre frequency, operating at several megahertz.

31. The input signal is first digitised and fed to a memory just as in the digital transient recorder. The memory output is a speeded up replica of the input signal. The speeded up digital signal is then reconverted to analogue form resulting in a signal which represents the sampled analyser input, but with a frequency translation of up to 500,000 times. Frequency and time being synonymous the output is a time compressed replica of the input. The high frequency analogue signal is then heterodyned with an internally generated carrier which steps in 250 - 1000 discrete steps. Each step produces a difference frequency at the centre frequency of the fixed filter, the output of which is R.M.S. detected and suitably averaged. A logic control array again permits outputting of the

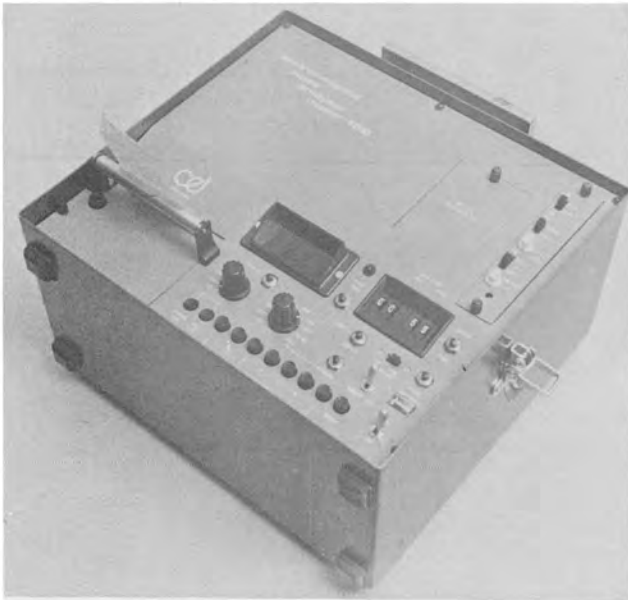
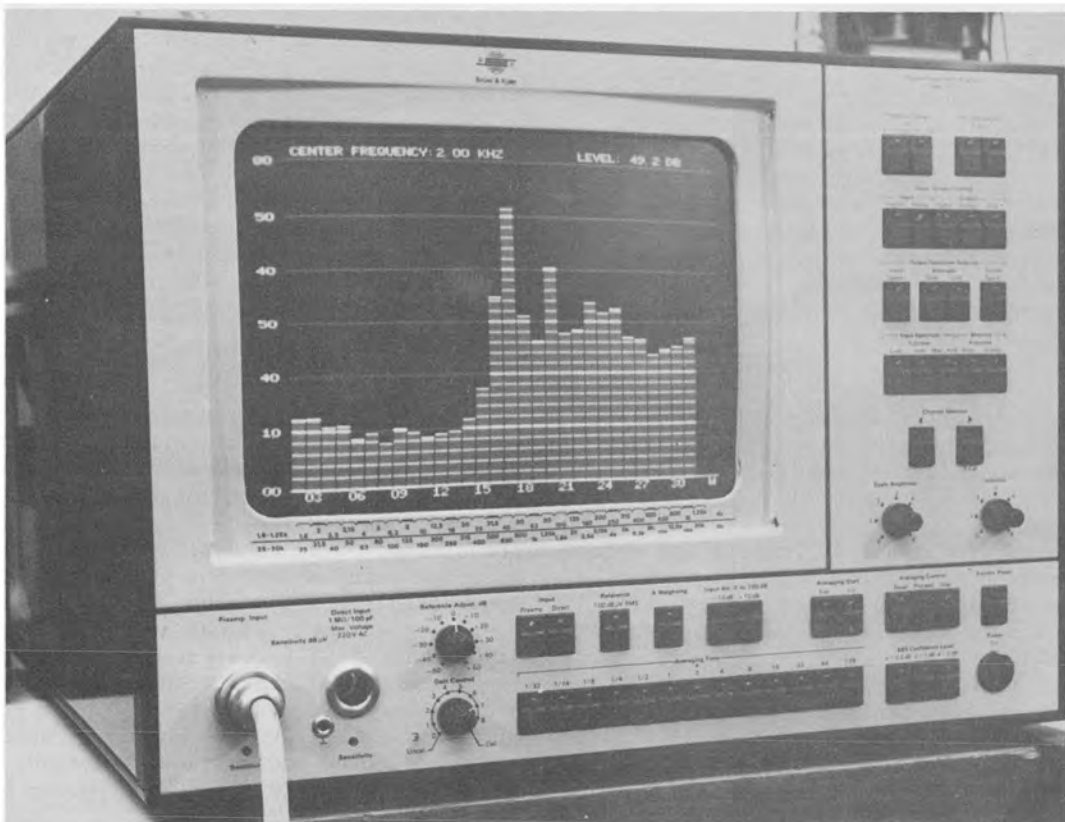


Fig. 1. Illustration of community noise analyser Type 162 which may be adapted for vibration use



Fig. 2 (right). PDP 11/40 installation which handles multichannel analysis tasks

Fig. 3 (below). 'State of the art' digital frequency analyser



completed spectra to various display devices.

32. The time compression analyser provides an extremely fast and efficient narrow band filter, so fast in fact that ensemble averaging is usually employed to improve statistical accuracy. Both the parallel filter and time compression systems have analogue filters and are subject to non-linearity in both amplitude and frequency.

Digital Filter Analysis

33. In the truly digital analysis (Fig. 3) the input signal is immediately converted to digital form and may never again emerge in analogue form. The filter itself operates digitally on the streams of binary words which comprise the frequency and amplitude information of the input data. The filter is normally of the recursive type, that is it operates several times on the same piece of data. Each signal path has delays, multipliers and summing nodes, the outputs of which are recombined with the original data stream. The composite output is then the signal which is confined in a rectangular slot in the frequency domain. Control of the whole system is done by a complicated pre-programmed logic array which outputs each complete and statistically defined spectrum.

34. The digital analyser is inherently more stable than its predecessors as all signals are simple binary on or off states, rather than time varying levels which have both phase and frequency. The system is independent of amplitude non-linearity except at the input analogue to digital conversion and at the analogue output. Frequency linearity is controlled by the internal sampling speed of the system, and this function is controlled to within a few parts in several million by a controlled crystal oscillator.

Mini Computer - and Microprocessor - The Final Word

35. In the final round-up we must again turn to the computer for the last word. It was briefly shown earlier how powerful this tool could be and again in the frequency domain it is just as powerful. Mini computers can execute all the arithmetic needed to complete the fast fourier transform algorithm. It can store spectra, add the subject, divide and multiply and perform a whole host of more complicated functions. It can predict trends and interpolate where data is missing. The "mini" can self check and command where necessary and it can communicate with larger installations with even greater capacity.

Conclusion

36. Advances in electronics have undoubtedly accelerated the development and manufacture of the instrumentation system described. Modern manufacturing has resulted in proliferation in certain areas, and much of the equipment designed for use in other fields of medicine, noise and data handling can be fully utilised by the scientists and engineers working in the field of ground borne vibration.

37. Portable analysis of great sophistication can now be taken directly to the measuring site and left unattended to collect and consolidate the data. Unquestionably we are moving towards a digital revolution where signals never appear in their original analogue states, and at the fore front is the microprocessor and mini computer.

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8. Specification of instrumentation for estimating and monitoring ground motion from earthquakes

R.E. LONG, BSc PhD (Department of Geological Sciences, University of Durham)

This paper reviews some of the problems facing a civil engineer required to specify a program giving pre and post design data for assessing the effects of ground motion from earthquakes. Some solutions to these problems as they affect seismic instrumentation are discussed.

1. The extent of a program to ascertain the risk of failure due to ground motions depends basically on the environment. A dam in a seismic region with a high population down-stream for example is clearly in a high risk environment and is a case where an extensive seismic program is justifiable. On the other hand, whereas no region can be regarded as totally aseismic, the program can be minimal in areas of low seismic activity. The following therefore outlines an overall strategy primarily intended for high risk zones which may be considerably reduced or augmented according to the environment.

2. The form of the data required of the seismologist cannot currently be defined in a general manner since various design techniques require different forms of data. The optimum interface between the design engineer and the seismologist is the subject of research at Durham and elsewhere. At present the design engineer, in consultation with a seismologist, must determine the appropriate form of the output according to the design problem. The nearest we can get to a general definition is that the data must describe in some way the time histories of probable ground motions over the lifetime of the structure.

3. The data splits naturally into two parts. The probability and spatial distributions of earthquakes occurring in the vicinity of site (normally established from regional and local seismicity studies), and the ground response at site to these earthquakes. Traditionally the former gives the probability for the latter.

REGIONAL SEISMICITY

4. Ideally regional seismicity should allow two important sets of data to be established. The first is essentially a three dimensional plot of events about site which should be related to the surface fault pattern. The second is the probability of events occurring in the vicinity of site as a function of size. Hitherto the measurement of size has been by magnitude which does not completely specify the observed seismic motion. At least two parameters are required for the complete definition. Seismic moment and

source radius are suitable parameters since they define the sources spectra.

5. Regional earthquake maps can be made using data from the world-wide network. This data generally only includes events of magnitudes above about 4.5 but depends on the region. The accuracy of the world-wide data is probably no better than 20 km in epicentre and where events are shallow gives no focal depth information. Local network can give focal depth data and better event location provided there is a sufficiently dense spread of stations. In many regions available data is insufficient to identify anything beyond the broad activity level of the region. In such cases some local network may be installed to augment the existing data.

6. The objectives of such a network may be summarized as follows:

- (a) to improve the accuracy of epicentral determinations which gives the detailed seismicity pattern relating to site and thereby improves the data on fault distribution and orientation and the nature of fault movements in the immediate site area (this should be coupled with geological observations);
- (b) to give details of expected depths of events (which are not normally well defined by world-wide or regional network data);
- (c) to augment the probability data obtainable from world-wide observations (and other local sources).

7. A problem in the use of regional networks is that the level of seismic activity varies with time. Activity normally consists of swarms of activity of relatively short duration distributed along the fault zone. Thus a zone is not observed to be uniformly active along its length nor is a section continually active in time. Superimposed on these distributed bursts of activity is a long term variation in activity level over the whole zone with a period of tens of years.¹ The problem with a regional network is therefore that they usually can only operate for a limited time period; probably two years as a maximum before design details are required by the client. Hence the statistical sample obtained by the network may not be representative of

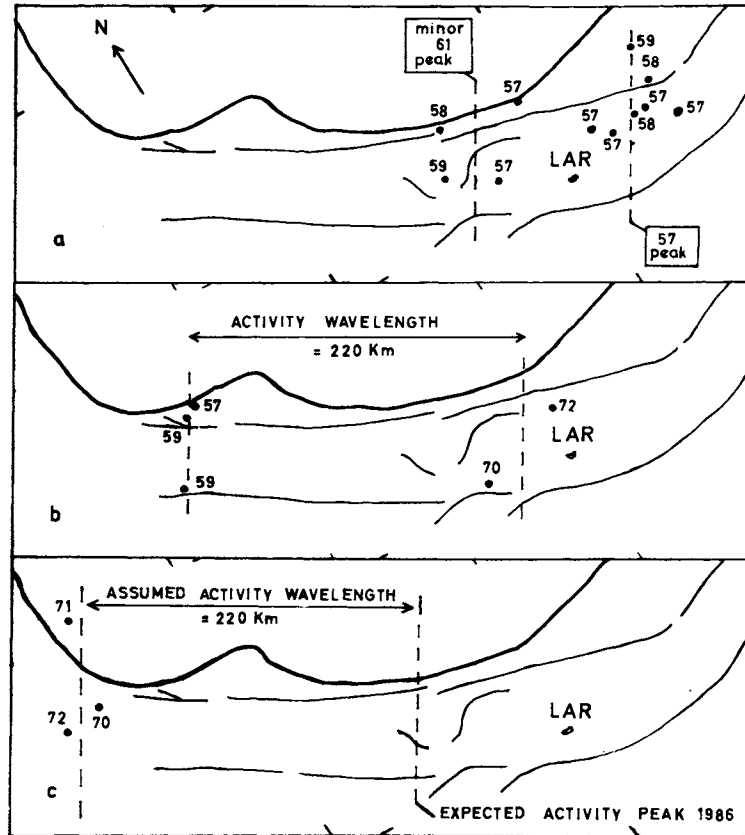


Fig.1. The temporal pattern of seismic activity about the site of the Lar dam in Iran which lies in a fault zone at the southern end of the Caspian Sea. This pattern may be associated with the 'flow' of activity across the whole of Iran, running from left to right of the figures. Bursts of activity occur at about 220 km intervals as each activity wave crosses the region (Fig. 1b) which allows the pattern to be projected to indicate future activity (Fig. 1c). Full details are published elsewhere²

the mean level of activity over the extended lifetime of the structure and some correction to the probability data is necessary. Such a correction may be estimated from world-wide data (though even this may be of short time period compared to some variation periods) and historical data when this is available. The value of the local network to probability data is therefore that it can provide the present magnitude-probability distribution probably more accurately than the world data, but it is essential that a correction be estimated for long term temporal variation since the aim is to establish mean probability levels over the lifetime of a structure which may be over several cycles of activity variation. Where a temporal pattern of activity can be recognised it should be allowed for (e.g. Fig.1).²

8. A partial solution to the problem of limited observation time has been to use sensitive instruments to record microearthquakes (magnitudes less than 1) which are more numerous than the larger events. However, this does not improve the temporal statistical data, only the number of events recorded, which improves the accuracy of the present probability measurements. Also the value of such observations to the engineer is limited. Since events are small they can normally only be recorded if they occur at relatively shallow depths and consequently they may not have the same depth statistics as the larger (i.e. the most dangerous) events. There is also the disadvantage from the viewpoint of assessing ground motion itself that the ground motion from such events is not readily scaled to the larger events. It is therefore considered that mid-range events (magnitude 2-5) are a better aim. In most seismic zones events in this range are normally sufficiently numerous for a useful output in a reasonably short time (of the order of a year). This can be checked from world-wide data. Clearly seismic investigations should be initiated as early as possible in any site evaluation program.

9. Such considerations clearly place limits on the sensitivity of the recording devices: too sensitive a device will saturate at the higher more useful magnitudes while too low a sensitivity would exclude the more frequent smaller events. Also the dynamic range (defined in decibels (dB) as $20 \log_{10} V_{\max}/V_{\min}$ where V is the output of the seismic detector) has a lower limit. If N is the difference of maximum and minimum magnitudes to be recorded then the dynamic range must exceed $20N$ dB which for the magnitude range 2-5 is 60 dB.

10. Since the position of seismic activity varies with time along a fault zone, it may happen that at a particular site the activity is currently low, although known to be active or likely to be active in the long term. In such a case a local network at site may not improve the earthquake probability data. However, a detailed observation of a swarm at some other point along the same fault zone may be useful in (a) establishing the time and frequency pattern of events in a typical swarm and (b) (to a lesser extent) the spatial pattern.

11. A regional network could be set up for this purpose. This is not necessarily more expensive than a local network at site. Generally, however, the regional network would have a wider spacing with long range radio links or separately recording instruments. If, however, an active region of the fault zone through site was evident at the time of observation, then a concentrated network in that region would be appropriate.

12. In the case of a site investigation for a reservoir where induced activity may occur then the expected induced activity may be modelled in the limit from a typical swarm characteristic. In this case, therefore, a swarm away from site can give valuable data on which to calculate expected activity at site. Thus at the site of the Lar reservoir (Iran) where a swarm is currently centred on site, observations can give ideal data on which to base a limit to induced activity. In fact on the pattern of Fig.1 the activity and therefore presumably the stress field will have reduced before fill in 1980 and therefore the induced activity may be less than that predicted from such a swarm.²

OBSERVATIONS AT SITE

13. The distribution of events about site gives the probabilities of events of varying size occurring at varying distances from site. To translate this data into probability-site motion data presents a problem which is not completely understood. A direct calculation is possible to give the order of magnitude of ground acceleration which is clearly too imprecise if such accelerations lie above 0.1g. This lack of precision arises principally from the fact that ground motion depends on local geology and topography. A change in near surface geology can show variation in peak amplitudes of an order of magnitude and can significantly change the time history of a seismic disturbance. Thus probable time histories cannot be generated without some information on site response.

14. The classical approach has been to select strong motion records with similar depths and distances to events observed and apply these time histories to check the design. But this ignores the effects of local geology and topography. An improved method is to use records for events not only with similar depths and distances but also from sites with similar geology. But again this is at best an approximation of the true motion and suitable data is not easily obtained.

15. Recent literature attempts to provide a set of standard curves of ground amplification as a function of frequency for various geological conditions.³ This approach cannot be completely successful since it ignores (as do the above record selection methods) the basic problem which is that amplification is fundamentally due to reverberation within the layered geology and is therefore critically dependent (at least in detail) on the dimensions and detail velocity variations of the near surface geology.^{4,5} For these various reasons it is clearly more



Fig.2. A portable seismic recorder designed for operation in remote areas. This equipment is commercially available

desirable if ground motions can be obtained by direct measurements at site.

16. A further reason for investigating the site response arises with large structures such as earth dams. Here the size of the structure and the size of the geology are of the same order. Thus an earth dam can be considered as a man-made hill extending the geology vertically. Hence in the dynamic design of such structures the structure and its geological foundation should be considered as one interacting vibrating system. For this problem sufficient data should be collected from site to allow this interaction to be included in design.

17. There are two broad methods of approaching these problems. The first is to determine the geological structure using seismic refraction methods. The output is a layered model where response can be calculated. An alteration to refraction would be borehole data if appropriate velocity logs were run which is not normal practice in site investigation. The second method is to directly measure the ground motion due to (larger) earthquakes.

18. The second is clearly the better method since it does not resort to a simplified model as is normally required in the first method and also may, if sufficiently high magnitudes happen to be recorded, implicitly allow for finite strengths of near surface rocks which are difficult to assess and use in calculated responses. The probability of recording large events close to site over the site evaluation period is however small. Some scaling of amplitudes may therefore be necessary to generate design motions. But the basic aim is to evaluate site response, and therefore the inaccuracy in scaling is offset by the advantage of having real site motion available for design. The second method requires instruments set up at site designed to record responses from magnitudes two or three, up to the highest magnitude expected. They should normally include strong motion devices and provide an output which is readily processed by computer, since some computer analysis of the records is an essential part of the design method.

19. In principle instruments at site could yield probability and site amplitude data directly, thus eliminating the requirement for regional or local networks. However, the regional pattern of activity is still required so that appropriate correction for the variation in the space-time pattern can be deduced. The regional network therefore still has a useful role in identifying the detailed earthquake pattern. Also local networks may still be considered useful in identifying local fault movements in the immediate site area.

POST-DESIGN DATA

20. Large structures should normally be instrumented for vibrations. The purpose is two-fold:

- (a) to check the design for possible vibrations which had not been foreseen and which might cause failure;

- (b) to provide data on which to base future design.

21. The instrumentation should be designed to record motions which could lead to damage. They should be placed in a structure at points where the designer considers accelerations are critical to stability. If this is not possible for reasons of accessibility, or if instrument damage is considered likely if failure were to occur, then the instruments should be placed at points from which the critical region can still be reliably monitored. The positioning of these devices should therefore be a by-product of the dynamic design of the structure. The designer can also give values of the expected critical acceleration at these positions and the instruments set to record over at least an order of magnitude on either side of this value, taking into consideration any uncertainty in the parameter used in the dynamic evaluation. Recorded accelerations are normally in the range 0.01-10g.

22. These instruments would normally not be continuously recording but be triggered when ground motion exceeded a certain acceleration.

23. Some countries, notably the USA, have networks of strong motion instruments (some in structures and some in open ground) which provide vibration information crucial to the problem of identifying near field motion from earthquakes. The number of near field observations is small. It is this fact more than any other which is holding up the satisfactory translation from event location probability data to probable site time histories. A major problem in site investigations is that a client cannot wait for the large events to occur. Thus data from such networks is crucial at least until some reliable method of calculation is developed.

SPECIFICATION OF FIELD INSTRUMENTS

24. Since processing of records is now an important part of site investigation methods, a recording medium which can be replayed directly into a computer becomes a pressing necessity. Many paper recorders also lack the dynamic range and wide frequency response required. Recording on magnetic tape is clearly preferable. Indeed if methods are to develop in the way they must if we are to have a reliable estimate of expected site motions, then the improved dynamic frequency ranges and flexibility of tape recording is a necessary requirement. Tape has in the past not generally gained acceptance in civil engineering recording because of maintenance and playback problems. Clearly it is useless to install complex electronic equipment without providing the level of expertise to keep it running and all too often the level of local expertise is low. On the other hand it is feasible to run complex devices serviced by relatively unskilled personnel if the level of equipment reliability is high and the required operator level sufficiently low. For example, a device may be designed with a high degree of sophistication and be a largely automatic device reducing operator interaction to a minimum, and which is sufficiently compact and cheap that sections can be

replaced if defects occur. Several manufacturers provide a replacement and maintenance service so that field equipment can be run on a replacement basis with periodic factory overhauls. Modern electronic equipment has over the years become cheaper and more reliable. Thus a recorder can be sophisticated with many automatic facilities without sacrificing reliability or making the machine prohibitively expensive. Thus the trend is to automatic devices as simple to use as a domestic radio or cassette recorder. The lack of local maintenance and electronic expertise need not necessarily exclude the use of electronics systems such as tape.

25. A suitable F.M. tape recorder is illustrated in Fig.2⁶ which was operated with success by totally unskilled native labour in Afar (Ethiopia). It is designed as an automatic instrument with operator lock-out from system set-up parameters so that unskilled operators can initiate automatic check routines but not arbitrarily reset gain or time for example. Completely automatic check-out facilities are available.

26. An important requirement of a field recorder is that it should be capable of recording for long time periods without servicing and without battery changes. Most sites in active regions are remote. Modern equipment is therefore designed to be of ultra-low power. The recorder of Fig.2 consumes only a tenth of a watt and will operate for up to a month from a set of in-

ternal dry cells. Similar equipment with external batteries has been operated for a year without battery changing or charging. In this respect the long playing time of modern tape systems is of definite advantage over paper.

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Discussion on Papers 7 and 8

MR MILES (Paper 7): The range of measurements required in the field of ground-borne vibration is immense. For example, the use of transducers on building foundations and walls is common when the buildings are in close proximity to piling operations, or perhaps the civil engineer wishes to know the impedance of a floor he has just built, or an architect may try to relate damage in the fabric of a monument with the passage of heavy road vehicles alongside it.

Choosing the right transducer is often difficult and confusing, especially for those not electronically minded. Should I measure vibration in terms of acceleration or velocity, or should I integrate from velocity to get displacement? What cables and signal amplifiers should I use? What effect will the environment have on my electronic measuring system?

Having decided that this is all 'mumbo-jumbo', and that we can record the data and let the electronics boys in the lab do the analysis, we ask more questions. How can we record the data - analogue tape, digital data logging or just plain UV recorder? Which magnetic tape system is best, FM or DR; what tape speed will I use; what frequency range can I expect?

Fortunately, though, most projects can be accomplished using simple portable vibration meters - or can they? For instance, the errors introduced by using filters, at low frequencies, with incorrect r.m.s. detector averaging times can be enormous. Unfortunately, manufacturers often omit to mention these points in the sales talk when you purchase the meter from them.

Returning to more complex analysis problems, say for mode plotting, or for source identification, where tape recordings have been made several analysis systems are available, and most of these are described in the paper. Also in the paper the adaptive use of instruments used in other engineering fields is described, to enable faster and easier analysis of some specific analysis problems.

In this day and age of computers, 'microprocessors' and 'minis', the last word must be given to these systems. Such digital devices tied into real-time analysers can provide all of the facilities found in the systems described, along with many arithmetic operations of high complexity.

DR LONG (Paper 8): The basic structure of the programme of investigation presented in the paper is illustrated in Fig.1. The three phases are

- I: seismicity studies
- II: site studies
- III: design.

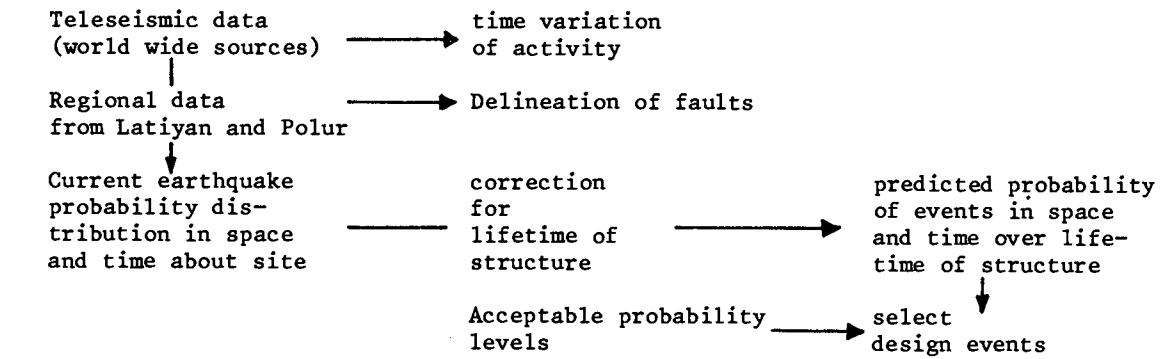
Equipment can play an important role in I and II. In both, the performance of the equipment in both dynamic range and frequency response is important to the interpretation of the data.

This may be illustrated for phase II. The processing of records for the direct analysis of site response can follow many of the processes used by geophysical prospecting companies in reflection interpretation. A simple example is the use of autocorrelation. In reflection interpretation this is used to detect multiple reflections (or reverberations) in near surface geology. Such reverberations are responsible for amplification of vibrations over layered geology; especially in soils where there is a high impedance contrast to the rock below. Fig.2 is an autocorrelation of an earthquake record at a site 20 km from the focus of a magnitude 2 event. The wavelet at the extreme left of the trace (zero time delay) represents the autocorrelation function of the received source pulse. Its repetition along the record indicates a reverberation in the near surface structure with a period of 0.6 s. The structure of the autocorrelation gives a direct measure of site response. Fig.3 shows reverberation more clearly as a discrete series of pulses. This is a small event giving low amplitude motions and yields the site resonances in these circumstances. Scaling the response to larger motions requires the non-linearity in the behaviour of the materials (particularly soils) to be taken into account.

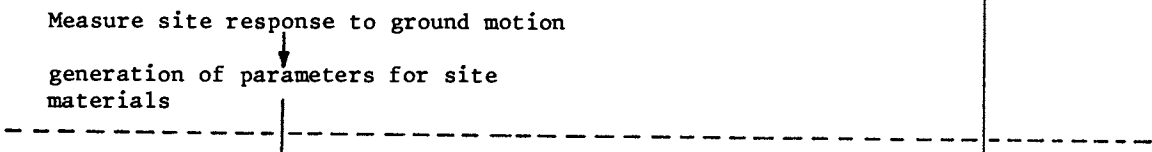
These techniques are, however, only possible if records are obtained with sufficient dynamic and frequency ranges and with minimal distortion. There is a general requirement in civil engineering work to use equipment with a much wider dynamic and frequency range than has hitherto been the practice. Clearly some computer-compatible record is required; tape is the obvious recording medium.

It might be of interest to relate the circumstances in which the equipment described in the paper was developed. It has been our experience that projects can fail if undue reliance is placed on generator or other accumulator charging facilities in remote areas. Hence a low power recorder is essential. The recorder described consumes 150 mW and is powered from internal dry cells for up to three weeks. Another important requirement is that it be portable and, to ob-

Phase I



Phase II



Phase III

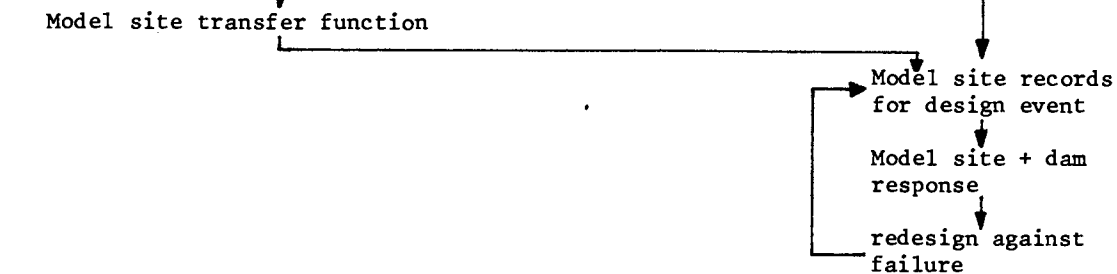


Fig.1

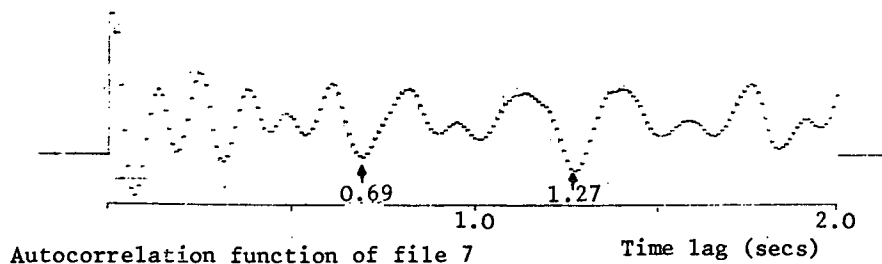
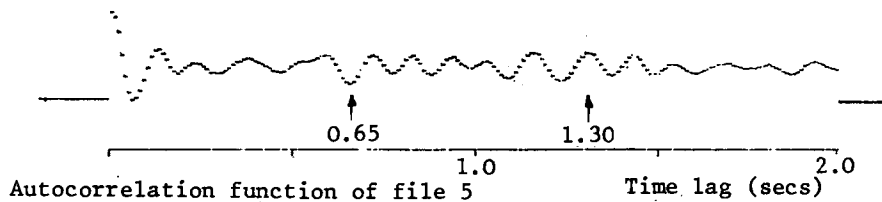


Fig.2

viate the need for skilled personnel to be on site for long periods, be reliably operated by unskilled personnel. The instrument is one of several installed by Durham staff and left in Kenya and operated successfully by local farmers and school teachers. The aim in design was to provide a simple easily understood system whilst retaining the quality of recording.

DR R.H. HELMY (The City University, London): How can we interpret a signal picked up by a transducer embedded in a partially saturated soil? For instance, how can we determine the particle velocity?

DR B.O. SKIPP (Soil Mechanics Ltd, Bracknell): It is desirable to couple the device into the ground with a recompacted sand (cf. discussion on Papers 9 and 10).

MR R. SIDNEY (Dames and Moore, London): Concerning reverberation phenomena observed in seismic records and their relation to site geology via an autocorrelation analysis procedure, would not a locally applied blast source be more appropriate for determining site characteristics? The resulting ground motion would be less influenced by other geological features not relevant to the site.

DR LONG: The requirement is to measure site response to motion that arrives from roughly the same direction as damaging earthquakes. Since the damaging earthquakes would lie at depth below site, explosive sources at the surface would not be equivalent unless a large explosion was let off at sufficient distance to allow waves to penetrate into the earth. This latter is not usually practical. Use of explosives close to site would be equivalent to a reflection or refraction experiment.

MR E.R. GILES (HM Inspectorate of Mines and Quarries, London): The instrumentation has become very sophisticated and it is possible to use wrong techniques.

To what extent is it possible for experts to disagree with each other?

MR MILES (Paper 7): The answer to the first comment can only be 'yes'! It is certainly my experience that as sophistication increases then so does the incidence of wrongful use, as a result of ignorance of the techniques involved.

One of the major problems facing engineers in all disciplines is remaining aware of current trends and techniques. As an electronics engineer I find this increasingly difficult owing to the exponential growth of the industry. I can therefore sympathize with engineers in other fields who find it difficult to remain aware of the advantages and limitations of the increasingly more complex equipment they are called upon to operate.

We must prevail upon the manufacturers of such equipment to provide more comprehensive manuals and training sessions, coupled with additional after-sales assistance.

In answer to the second matter, surely this is a major reason for learned bodies and their members continuing to arrange conferences and symposia in related fields. The valuable exchange of ideas and information which occurs at these functions must be encouraged to continue.

DR P. SRINIVASULU (Structural Engineering Research Centre, Madras, India): In §20, Mr Miles refers to two civil engineering applications for the use of vibration energy meters - one for assessing the vibration effect of wind on church spires and the other on the effect of pile vibration on a building foundation. Would he please clarify how the energy limits of vibration in

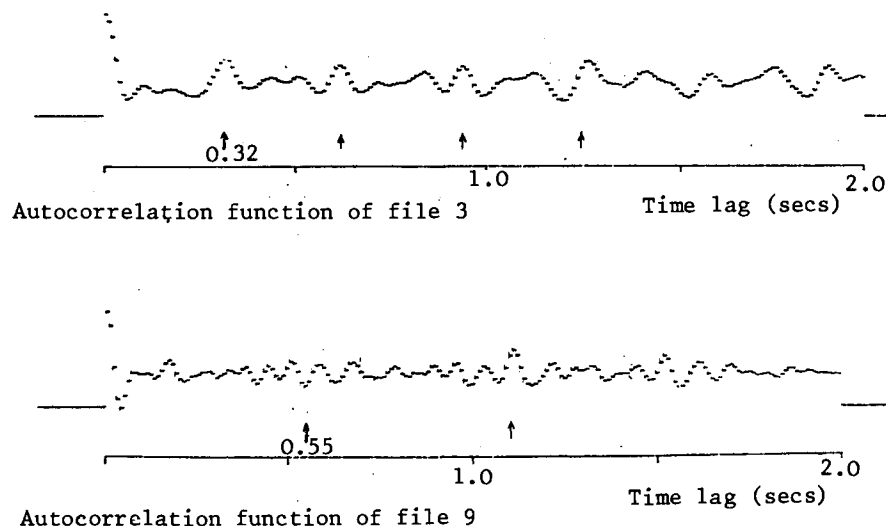


Fig.3

specific units are related to the degree of damage? References to these sources, not quoted in the paper, would be informative.

Can the author throw some light on the minimum length of input vibration record necessary for the spectrum analyser to yield a reasonably accurate representation of the resonant frequencies (up to, say, 200 Hz) in the frequency spectrum plot it gives?

MR MILES: The use of energy-measuring devices, such as the Bruel and Kjaer community noise meter and the CEL noise average meter, connected to an appropriate vibration transducer was mentioned because the author has long felt that the r.m.s. energy of a vibration signal into a structure could be related to visible signs of damage to the fabric.

To an extent this can be backed up by work done by the Wolfson Unit of Southampton University and other bodies in connection with road traffic vibration and the effect of sonic boom on structures. Unfortunately, most of this work has been limited in scope by the constraints of the consultancy project involved and hence to this date little has been published on this aspect.

The raising of this point was intended to promote discussion in this area; and perhaps a wider interest in the adaptive use of energy-measuring systems could, thus, be looked forward to, with the prospect of a greater knowledge of damage mechanisms.

The length of the vibration record required for a particular analysis is dependent on the tolerable error bound for the analysis and on the type of filter used in the spectrum analyser. In general terms the expression given below relates the acceptable error to the analysis bandwidth and the record length, or more correctly the averaging time of the r.m.s. detector used in the analyser:

$$\epsilon = \frac{1}{2(BT)^{\frac{1}{2}}}$$

where ϵ is the error bound, B the analysis bandwidth and T the averaging time (in seconds) of the detector.

If the record length is only equivalent to the averaging time then statistically this yields a 63% probability of the error lying inside the limits set for ϵ .

Alternatively, if the analyser is of the swept type associated with a chart recorder, a good rule of thumb to adopt is to make the record length at least twice as long as the time required for the chart to traverse one bandwidth of the analyser at the intended chart speed. The chart speed itself can be optimized by calculation but should never exceed the speed required to traverse one bandwidth during one averaging period of the r.m.s. detector. Using a slower speed and taking more 'distributions' increases the probability of the error being inside the stipulated limits.

MR I.P. HAIGH (Sir Alexander Gibb and Partners, Reading): After listening to the discussion, I

am left with some doubts as to how far civil engineers in the ordinary course of their work and with no special training in electronics should be encouraged to make direct use of instruments to measure vibrations in any form. Are the instruments now available sufficiently robust, reliable and simple to be used by the inexpert, or should civil engineers, as is their practice at present, continue to rely on specialist assistance?

Instruments for all purposes are proliferating, and it is difficult for consulting engineers, working as partnerships, to purchase for their own use as many instruments as they would wish. In the vibration field, are manufacturers arranging finance to hire instruments to occasional users?

DR P.L. WILLMORE (Institute of Geological Sciences, Edinburgh): I think it a major defect of our educational system, from comprehensive school through to the technical colleges and universities, that industry is so poorly supplied with people who have a good general grasp of the principles of physics, chemistry and engineering, so that we now have a population which can mass-produce all sorts of black boxes without really understanding what they do. I have now had three lots of central heating installed by 'specialists' who have revealed, in such simple matters as the distribution of insulation along pipe runs, that they have a basic ignorance of the conditions for thermal convection. I think there is a great deal to be said for making good equipment more widely available by hire, or by reduced capital cost from simpler or larger-scale production - but one would be happier if every potential user, down to quite a junior level in the design office or on the construction site, understood such things as the equation of motion of the simple pendulum or the perils of peak reading from transients in the presence of sharp filters.

DR LONG: In seismology, where networks of seismic stations are set up to monitor earthquakes for relatively long periods, field running costs can be expensive. For this reason we have developed equipment which can be used by inexperienced personnel to obviate the need for an expert to be present continuously. Similarly, on a civil engineering site it is often impracticable to employ a man solely for equipment operation. Equipment should, therefore, generally be such that the Resident Engineer or an assistant can readily operate it. The design should present a simple and direct interface to the operator so that training problems with unskilled personnel are reduced. This applies to operation of the equipment and not to the selection or to installation and subsequent use of the data. In each of these some expertise is required. It is therefore satisfactory to hire equipment provided that its use and function is understood by the consultants and they have the expertise to install and interpret. Otherwise this expertise must be hired as well if reliable results are to be obtained.

9. Use of vibration monitoring on offshore structures

L.R.WOOTTON, BSc PhD MICE MRAES (Atkins Research and Development, Epsom)

Monitoring the dynamic response of steel offshore platforms is now being used to detect changes in the structural integrity. The work involves comparing accelerometer measurements taken on the deck or on the structure in the splash zone with calculated and previously measured response modes. The analysis falls into two parts; discerning that a change has occurred and then diagnosing the form of the failure and its position.

INTRODUCTION

1. Whilst the initial design and construction of offshore oil-production platforms present prodigious engineering problems, it is now clear that their inspection and maintenance represents no less a formidable task. This paper discusses the developments that have taken place in the use of vibration analysis techniques to discern structural failures and indicates the way in which these techniques can be applied more widely.

2. Fixed offshore oil-production platforms are fixed structures which are of two basic generic forms: steel lattice structures that are lightweight and have to be piled into the sea bed to resist the overturning motion due to the wind and waves and concrete structures that rely on gravity forces applied over a large base for structural stability. The work that is described here is related to steel structures.

3. A typical northern North Sea steel jacket (Fig. 1) comprises a few hundred steel tubes joined at nodes to form a braced lattice. The jacket surrounds a bundle of conductor tubes which bring the oil to the surface. The design and operation of the platform (the word 'platform' refers to the complete jacket, conductor tubes and deck equipment) in UK waters are controlled by the Mineral Workings (Offshore Installations) Act (reference 1) and this requires a substantial annual inspection and a complete inspection every five years. In practice neither are attainable by conventional visual, photographic or non-destructive testing methods without a vast amount of diving time and associated expense.

4. It has therefore been necessary to develop a technique that will replace at least some of the diving effort by discerning those parts of the structure that have lost strength. The principle is to monitor the statistical properties of the response of the structure to environmental loads, using several accelerometers, and look for changes over a long period of time. By comparing each set of response

data with calculated predictions and with previously measured sets it is possible to tell if the structural stiffness has reduced perhaps due to a member losing strength or, indeed, missing completely. The two major technical problems are the vast amount of data that is acquired and processed (typically 10^{10} numbers per year) and difficulty of associating the changes in the statistical properties of the signals with specific parts of the structure.

THE MEASUREMENT SYSTEM

1. The instrumentation may be considered as related to three categories of data: meteorological, environmental and performance. A general layout of an instrumentation system is shown in Fig 2. The meteorological data (e.g. wind speed and direction) is used for weather forecasting and for comparing the actual weather with the predicted long term climate. The wind speed can be measured using a conventional cup anemometer and the acquisition of the other properties requires no specialised equipment.

2. The environmental data has more direct relevance to structural monitoring. One system of monitoring is to assume that the static and dynamic structural analysis together with the fatigue work carried out during the initial design are essentially correct and that the only unknown factor is the imposed environmental loads. Thus, if the actual wave conditions are measured then the fatigue analysis can be updated every few months and the structural damage assessed. Clearly, such a scheme is based on a number of assumptions; for example that the jacket has been constructed and welded precisely as was intended and that the conversion from sea state conditions to forces acting on the jacket can be calculated precisely. However inexact this method may be, it does provide a useful guide to the progress of the structure.

3. The basis of environmental data is the wave condition. The water surface movement is



Fig.1. The BP Forties FB platform leaving Greythorpe yard in the horizontal position prior to its rotation and erection offshore. (Photograph: John Laing and Sons Ltd)

used for the calculation of the maximum, r.m.s. and other representations of wave height and zero-crossing period. It is best obtained from a wave staff fixed to the structure. This comprises a taut wire or wires running vertically through the splash zone and which are used to measure the elevation of the water surface by conductivity or capacitance. Such a system can be installed easily during the construction of the jacket. Alternatively, since it can be very difficult to fit a staff to a jacket already in the field, instrumented buoys are also used to measure water surface elevation. Neither instrument indicate the direction of travel of the waves and, indeed, this is quite a difficult property to sort out. Any particular sea state may comprise of waves from several different directions; for example, in the North Sea, long period swell from the north may occur simultaneously with shorter period locally generated waves from the west. One technique that can be used to derive directional spectra is to fit an electromagnetic current meter about half-way up the structure to measure the resultant horizontal velocity vector of the water particles. The steady currents, for example, due to tides and Coriolis force, must be subtracted as a separate item so that the directional wave spectrum may be derived.

4. Environmental data also provides an important basis for cataloging vibration data. The response of the structure depends on the spectrum of the wave conditions, including directional information, the tidal current and the wind. The most important part of the performance is the measurement of the accelerations at key points near the top of the structure. The most suitable accelerometers for this work have a working frequency range from static to about 100 Hz and have a very high sensitivity to cover the full dynamic range of motions that occur. The positioning of the accelerometers and the analysis is discussed later.

5. A wide variety of other performance data such as strains, forces on members and soil pressures can be measured, though usually this is only used as a part of an extensive study on the design process or for other scientific investigations. The wider application of offshore measurements including their use in the implementation of an innovative design is discussed in reference 2. As with all offshore instrumentation, much of the cost is associated with the cabling and installation particularly if carried out offshore.

6. For monitoring purposes it is usual to record the data for periods of about 20 minutes every six hours but perhaps less frequent recording during very calm periods. The data is not processed on board the platform but, instead, is recorded on a tape recorder and the tapes carried to a land-based computer. A high density pulse code modulated (PCM) sampling and recording system is used because of the large amount of information that must be collated. There are a number of reasons why on-board computation of the results, which could give

instantaneous warning of the failure of a member, has not been used so far. The analysis is complex and requires a significant amount of intervention by one or two highly trained dynamicists if the full value of the information is to be derived and it is not practical to employ such staff offshore. In addition, accommodation for staff and facilities is severely restricted, particularly during the first few years of drilling and commissioning. Finally, at the moment there is concern that any automatic on-board system that gives a red light "Abandon Jacket" warning unnecessarily could bring the whole scheme into disrepute. In practice, the delay in analysing the data is not thought to be very significant; most structural failures generally occur over a fairly long time period.

METHODS OF STRUCTURAL ANALYSIS

1. The accurate dynamic analysis of the jacket structure is very important in determining firstly the most suitable positions for the accelerometers on the jacket and then the likely cause of any particular measured change in the vibration response. In addition to the usual problems of accurate modelling of the structure and, particularly, the soil and pile stiffnesses and effective masses, marine structures have the additional complication that the added mass of water must be modelled. For a circular cylinder, the effect of the water is to increase its mass by the mass of water it displaces when it oscillates in a direction that is normal to its axis. Any motion along the axis of the cylinder does not entrain water: hence the added mass is vectorial.

2. The most common method of dynamic analysis is by finite elements but since this technique is well established, it is not described in detail here. For structural monitoring, an alternative approach, using the dynamic stiffness method has certain advantages. In this method, the members of a frame, such as a steel jacket, are represented by continuous beams not isolated masses and stiffness points. The accuracy of the calculation does not decrease with higher modes as it does with the finite element calculations for example. Also, it is possible to calculate higher mode shapes and frequencies without starting sequentially with the lowest. This feature is important when calculating the response of a jacket with a failed member. Details of the dynamic stiffness method are given in reference 3.

3. The response of a steel jacket in the first three modes and three higher modes is shown in Fig. 3. The three lowest modes involve considerable movement of the piles and the structure almost moves as a rigid body. Such modes are of little use in structural monitoring. However, the 4th mode is a vertical bouncing mode of the lowest horizontal frame, whilst the next mode is a twisting mode of the same members. Any change in the measured values of the natural frequencies of these two modes would naturally be associated with a change of this area of structure and would enable a diving inspection

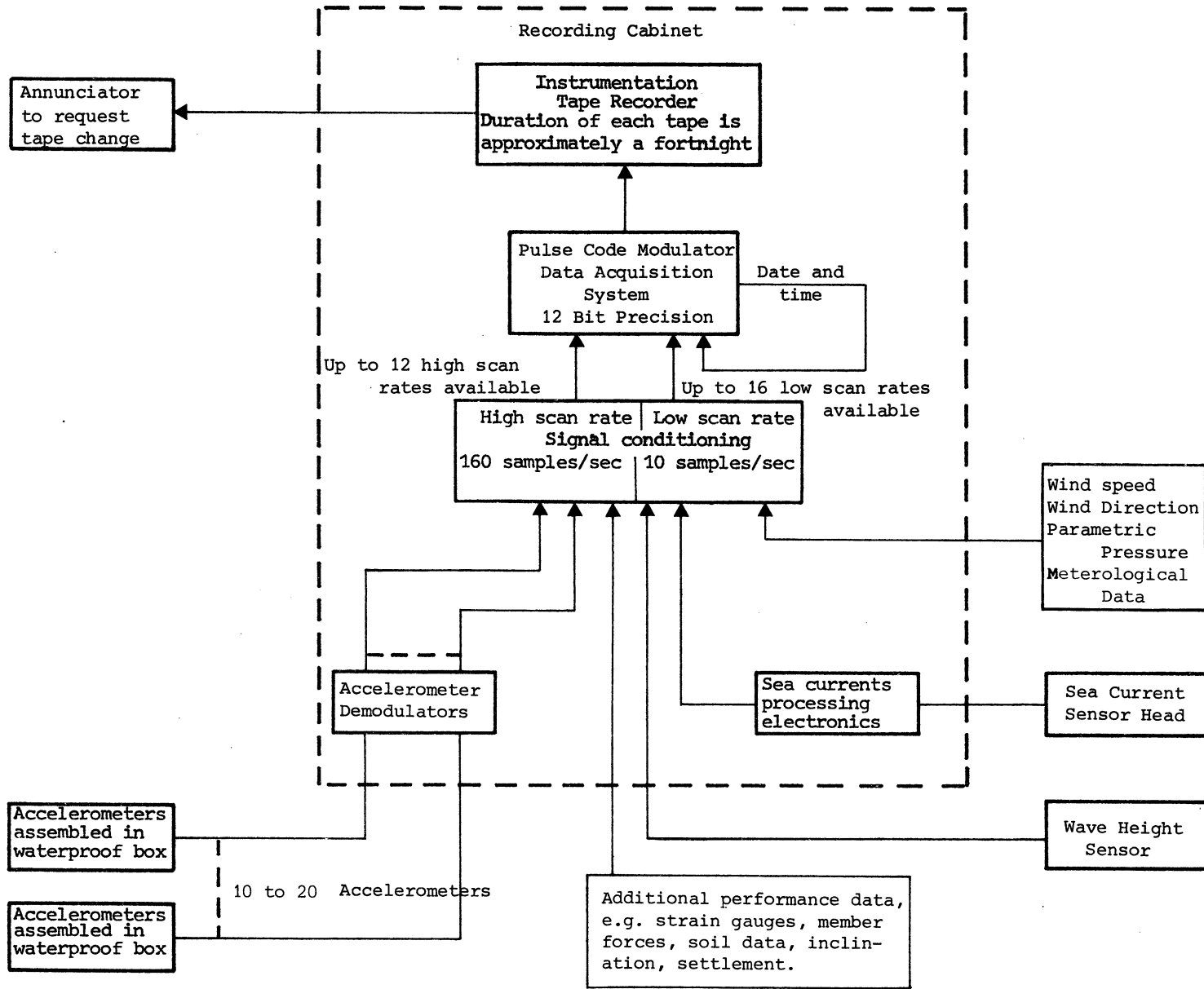


Fig.2. Layout of instruments on jacket

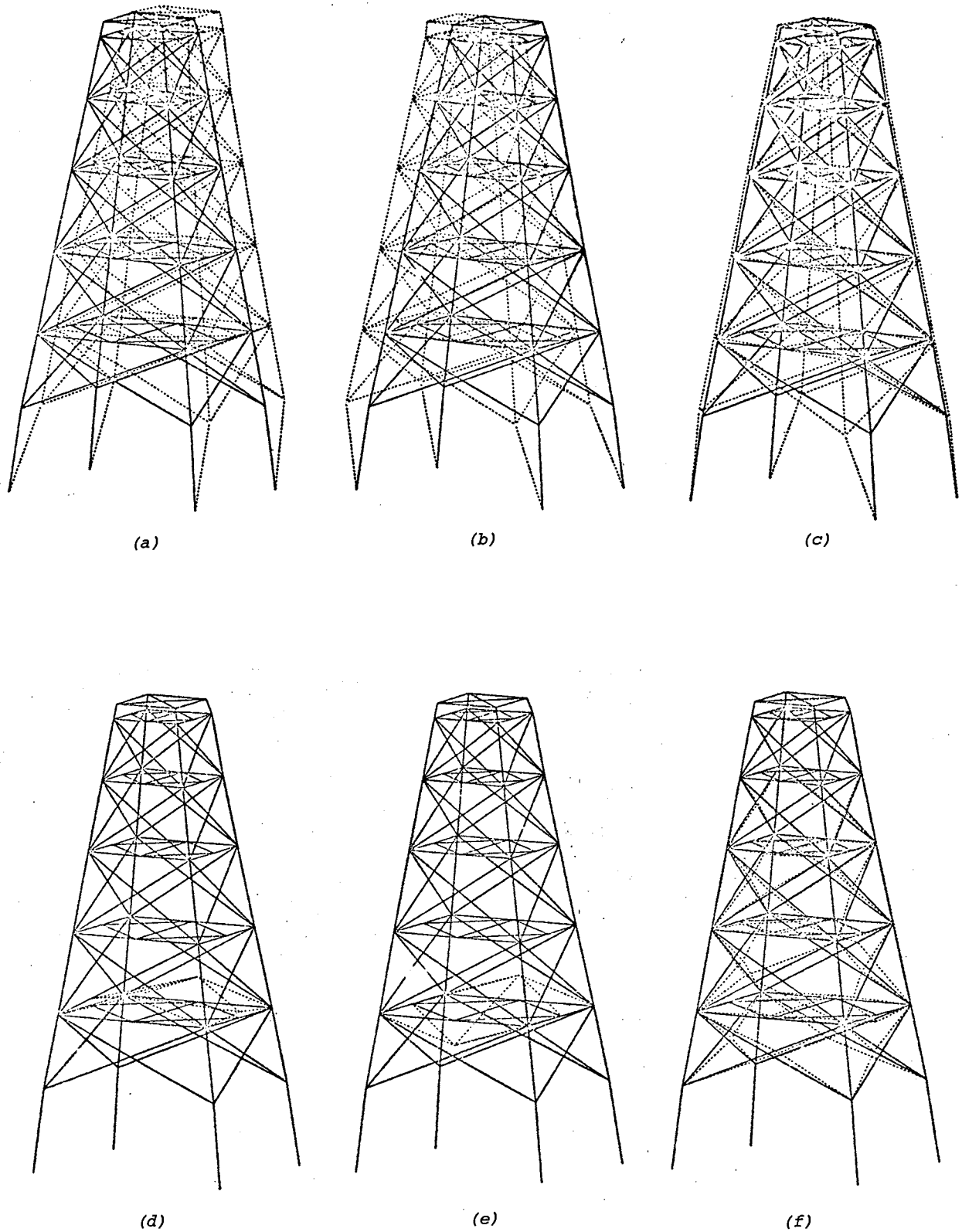


Fig.3. (a) mode 1, $N=0.50$ Hz, sway in x direction; (b) mode 2, $N=0.58$ Hz, sway in y direction; (c) mode 3, $N=0.98$ Hz, torsion; (d) mode 4, $N=1.39$ Hz, horizontal brace bounce; (e) mode 5, $N=1.79$ Hz, horizontal brace warp; (f) mode 14, $N=2.75$ Hz, breathing mode



Fig.4. Model of a steel offshore platform under test to study vibration modes

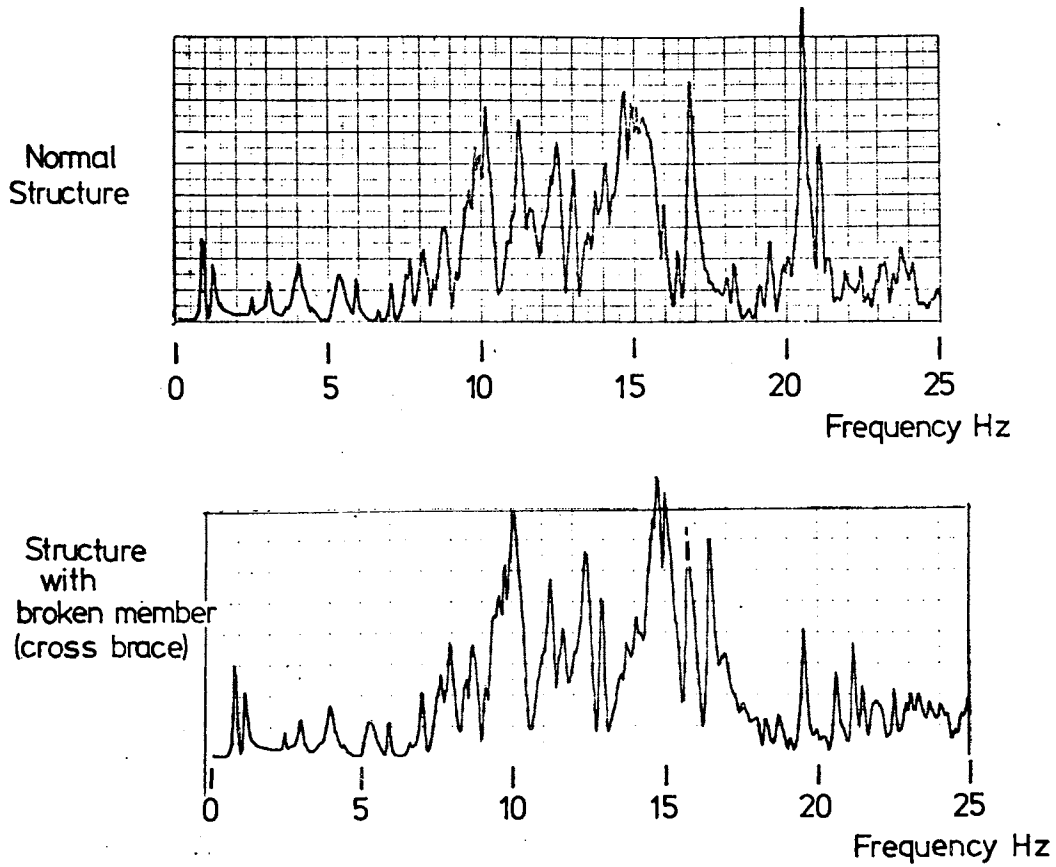


Fig.5. Spectra measured on model offshore jacket

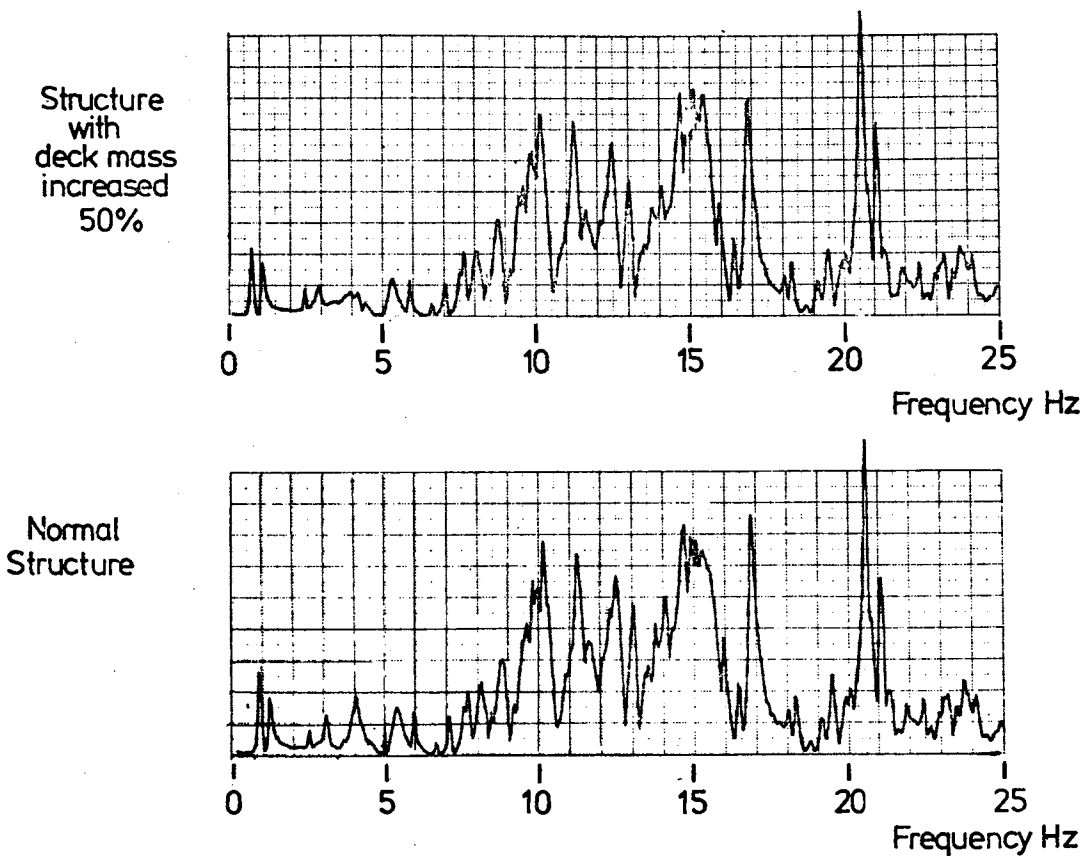


Fig.6. Spectra measured on model offshore jacket

to be concentrated in this area. Similarly other parts of the structure have modes that make it possible to discern changes in stiffness there. In an efficient jacket design all members that are providing strength also provide significant stiffness, which may be measured in the vibration characteristics. A few members may have been inserted to provide stiffness and strength during the launch and up-ending of the jacket and in the final condition may be redundant. It is axiomatic that, whilst their loss might be unnoticed by the vibration monitoring technique, their loss will not significantly reduce the overall reliability of the structure.

METHODS OF ANALYSIS

1. A real offshore platform is excited by a wide range of fluid-dynamic and some mechanical dynamic forces. The predominant force, due to waves, is experienced by all the members of the jacket below the water. The frequency of the force is that of the wave spectrum, which is fairly narrow, plus certain additional frequencies due to non-linear relationships between water surface elevation and force. In addition, vortex shedding from the individual members, wave slam and slap at the water/air interface and turbulence in the tidal flow almost produce dynamic loads with energy at a wide range of frequencies. Wind on the superstructure is another form of dynamic load but is less significant for structural monitoring. The regular dynamic loads due to the on-board machinery (turbines, pumps, cranes etc.) tends to be at frequencies that are significantly higher than those used for monitoring but in any case their strong periodicity makes them readily identifiable in the measured spectra.

2. The first level of analysis of the data from the accelerometers is a straight forward spectral approach. Two spectra, taken from a model of a steel jacket (Fig. 4) are shown in Fig. 5. There is a reduction of the spectral peak at about 20.5 Hz when one of the lower diagonal members is broken. One potential problem is that the same order of change in the spectrum could be caused by factors other than a change in a structural member. For example, marine growth increases the weight of a structure by increasing the added mass but this effect develops very slowly. Changes of top deck mass distribution can be much more sudden, the loading of pipes from a supply vessel for example. However, as Fig. 6 shows, it is fortunate that the deck mass has little influence on the

response of most modes since there is little deck movement.

3. The two spectra shown in Fig. 6 are almost identical except for the very lowest modes.

4. A point that is of particular importance is the possible detection of cracks; that is, the detection of the reduction in bending stiffness of a member that is effectively still carrying full axial load. On the model shown in Fig. 4, this situation has been detected but on a full scale structure this will only be possible for certain members which contribute significantly to the overall stiffness.

5. The scheme is that response data are compared with data obtained under similar loading conditions, that is similar wave heights, periods and directions. In practice many of the modes of oscillation of the structure are not significantly influenced by the direction of the waves that are exciting it but the cataloguing system is still used. Any changes in mode shape or response frequency can be discerned by reference to the spectra directly or by special techniques that have been developed to display small changes.

6. The purpose of this initial condition monitoring is to discern any change in the structure; if there is change then the cause must be diagnosed. Very careful analysis of the data already already acquired will probably locate the damage to within a few members on a certain area. From this point, traditional non-destructive testing techniques can take over.

7. There is no doubt that monitoring of the dynamic response of an offshore structure can provide an efficient system for the monitoring of its structural integrity. The techniques that are currently being evolved may have much wider application.

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10. Some experiences in ground vibration monitoring

J.S. BUCKLEY, BSc MSc and J. SMITH, BSc MSc (Soil Mechanics Ltd, Bracknell)

To be commercially viable a ground vibration monitoring operation has to have equipment that combines a high technical capability with flexibility and high utilisation of individual components. This paper discusses the options that are available and illustrates the authors choice of instrumentation with three case histories.

INTRODUCTION

1. Any responsible company in the ground vibration measurement field has several interacting factors to consider when establishing an instrumentation system. Firstly the system must be capable of faithfully capturing the ground motion; secondly it must be flexible enough to cover all the requirements of the market and thirdly economics dictates that each component must have a high usage rate. This paper discusses how these conditions must be met and illustrates with three case histories the versatility obtainable from a limited amount of equipment.

Detectors

2. In order to completely define the ground motion at a point it is necessary to faithfully measure, both in amplitude and frequency, three orthogonal components either in terms of particle displacement, velocity or acceleration. As most displacement transducers are only sensitive to very low frequency inputs then for practical purposes the choice of detectors is between geophones and the commonly available piezoelectric accelerometers.

3. Geophones are essentially robust instruments having a wide dynamic range. As such they have obvious appeal. A limitation on their use however is that their response to frequencies below about twice their natural frequency is reduced in amplitude and distorted in phases. This is also compounded by the fact that those models with natural frequencies below 4 Hz are unwieldy and not suited to the high mobility and ease of installation demanded by a commercial operation. The upper limit on the usable geophone frequency range is characteristically only about 200 Hz. This however is not a problem as ground vibrations, except when blasting in hard rock, seldom have frequencies in excess of this.

4. By comparison accelerometers have no low

frequency limitations giving excellent reproduction typically over the range 0.1 Hz to several kHz. A restriction on their use however is that those having a sensitivity suitable for measuring down to low 'g' ground vibrations have such a restricted dynamic range, typically 1 'g', that they are of limited use in measuring close to a source or where high vibration levels are expected.

5. The compromise used by the authors is to preferentially use critically damped 4.5 Hz natural frequency geophones but where it is suspected that low frequencies are likely, to monitor in parallel with accelerometers to assess the low frequency content of the vibration. Whichever detectors are used the authors would stress the significance of proper coupling to the ground or structure to avoid the introduction of spurious frequencies and attenuation or magnification of the vibrations.

Recording system

6. The choice of a suitable recording system to meet all requirements is not so simple as for detectors as there is a greater range with each system perfectly suited to a limited operational capability. The simplest is a hand held moving coil type meter to which a detector is attached. This is quite acceptable where a periodic source, for example ground vibrations from machinery, is being studied as time permits the correct measurement range to be found. However in order to monitor transient vibrations, such as from a piling hammer, this meter type of system is not suitable as a broad band recording system is needed. One alternative solution is to use an accelerometer connected to a peak level measuring circuit so that a simple meter can be used to read a resultant DC signal. Obviously no frequency information is gained but the system is simple, cheap and portable. The next stage of sophistication is a system in which permanent record on heat, electro or pressure sensitive paper is obtained of the peak vibration level.

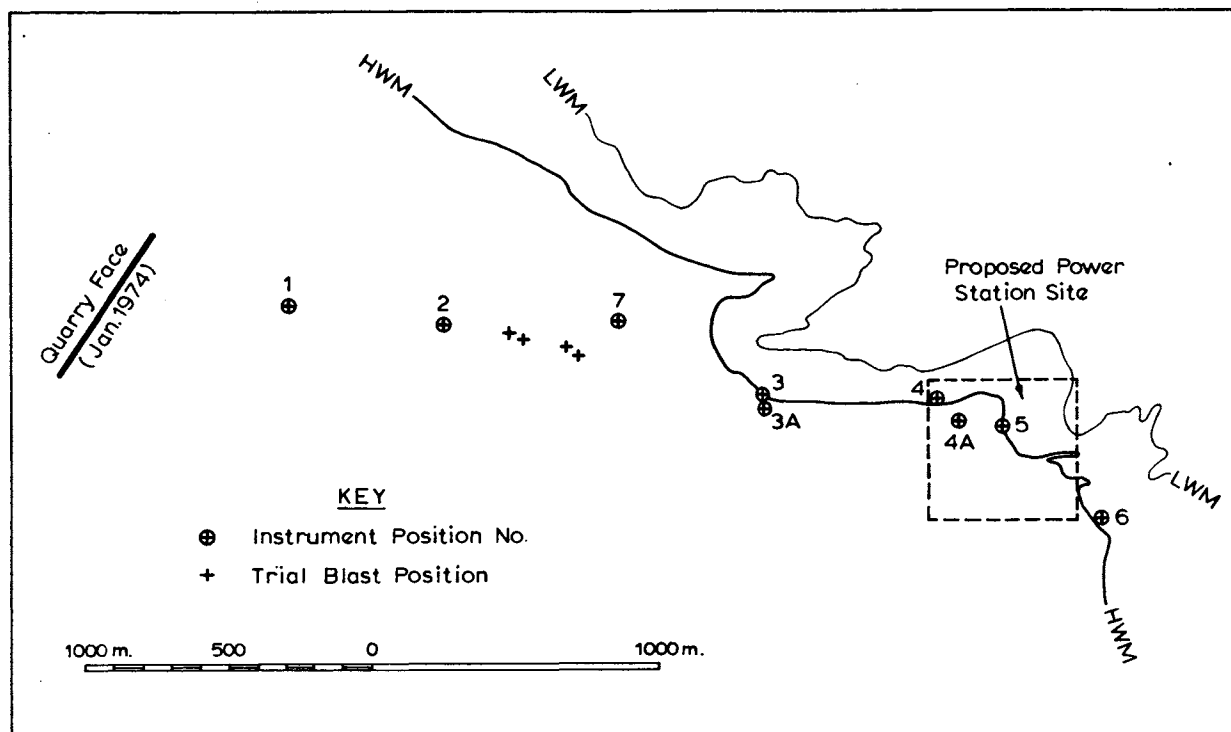


Fig.1. Torness Point site plan

With experience an appropriate scale can be chosen to allow its use in "one off" source monitoring but again no information on frequency content or vibration duration is obtained. These limitations are removed if instead a recorder is used with a sufficiently high chart speed to permit recording of a complete "wiggly" trace. Points against this system are that recorders of the pen or stylus type normally have a maximum of 4 input channels and an upper frequency limit of about 70 Hz. These can be overcome however by using an ultra-violet recorder which typically has an upper frequency limit of about 700 Hz and can have as many as 24 channels.

7. Whilst in many ways a real time visual record is attractive the possible wide range of input vibration amplitudes found in many monitoring exercises makes successful collection of data in this manner very difficult. The necessary recording system for an all round monitoring capability is therefore an F.M. tape recorder preferably having a minimum of 7 channels. A unit of this type typically has a dynamic range of 48 db and with a tape speed of $7\frac{1}{2}$ ins per sec a frequency range of DC to 2.5 kHz. It thus can faithfully record all expected signals. The disadvantages of such a system are the cost when combined with a visual replay system and the reduced portability that results. Overall however the authors consider that the technical advantages far outweigh the financial and operational disadvantages and for most of their monitoring use a 14 channel tape recorder combined with a 6 channel ultra-violet galvanometer recorder for parallel recording and playback of the data.

CASE HISTORIES

8. The case histories that follow demonstrate how with a basic system of low frequency geophones, accelerometers, 6 channel ultra-violet galvanometer recorder and a 14 channel F.M. tape recorder a wide range of commercial vibration monitoring exercises may be successfully carried out to a high technical standard.

Torness Point

9. Torness Point is a headland about 8 kilometres east of Dunbar, East Lothian which in the early seventies was selected by the South of Scotland Electricity Board as a possible site for a nuclear power station. A unique aspect in assessing the suitability of this site was the necessity to consider in detail the possible effect on the relays and safety circuits of the ground vibrations set up during blasting operations at a nearby quarry (Fig. 1). The necessary study had not only to consider the present day risk but provide data for drawing up guidelines for limiting future encroachment of the quarry face towards the power station.

10. Factors which had to be taken into consideration in designing the programme of measurements were:-

- (i) a present day quarry face - site separation of 3.5 kilometres but if future development were approved the quarry face could encroach to within 1 kilometre of the site.
- (ii) maximum charges at present of 8000 kg but future quarrying would probably involve blasting in a particularly competent sandstone in the local succession which it was thought would require heavier charges.
- (iii) the power station was likely to have structures founded both on the local glacial deposits and the underlying Carboniferous limestones and sandstones.
- (iv) basic data from the exercise could be required at a future date for re-analysis by an independent body.

11. It was therefore decided to base the measurements on the derivation of a ground vibration attenuation with distance relationship for the site and to investigate the significance of the drift and future blasting in the more competent sandstone with additional measurements. The recording positions between the quarry and site, (Fig. 1) were chosen as a compromise between a logarithmic spacing and access. At those positions along the coastal cliffs the detectors were placed both on the rock exposed on the shore line and in the glacial drift at the top of the cliffs.

12. Because of the large distances and number of recording channels required, simultaneous recording at all stations was not attempted and instead, measurements were made at two positions for each blast. At each position two sets of triaxial sensors were installed; one set being 4.5 Hz natural frequency, critically damped geophones and the other low 'g' accelerometers. In order to ensure faithful reproduction of the ground movement sensors on the drift were buried about 0.5 metres deep whilst for positions on the rock the possible effect of a weathered layer was removed by clamping the sensors to a concrete block which was tied to the rock by three anchors extending at least 2 metres into the rock. The outputs from the head amplifier with each sensor were recorded on magnetic tape and in parallel on ultra-violet galvanometer recorders.

13. In addition to monitoring nine quarry blasts, measurements were also made at Position Nos. 3 and 7 during a series of trial blasts of up to 22 kg of explosive detonated in the competent sandstone at the

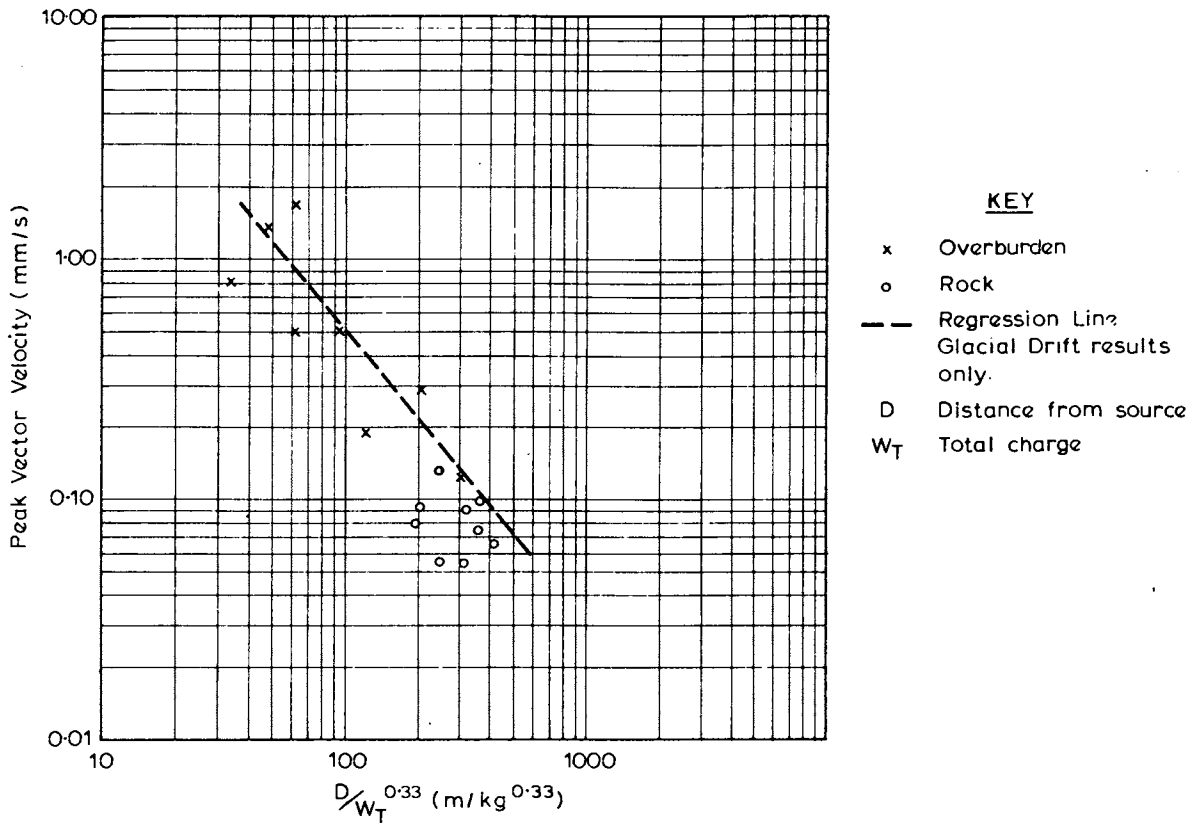


Fig.2. Peak vector velocity versus scaled distance, Torness Point

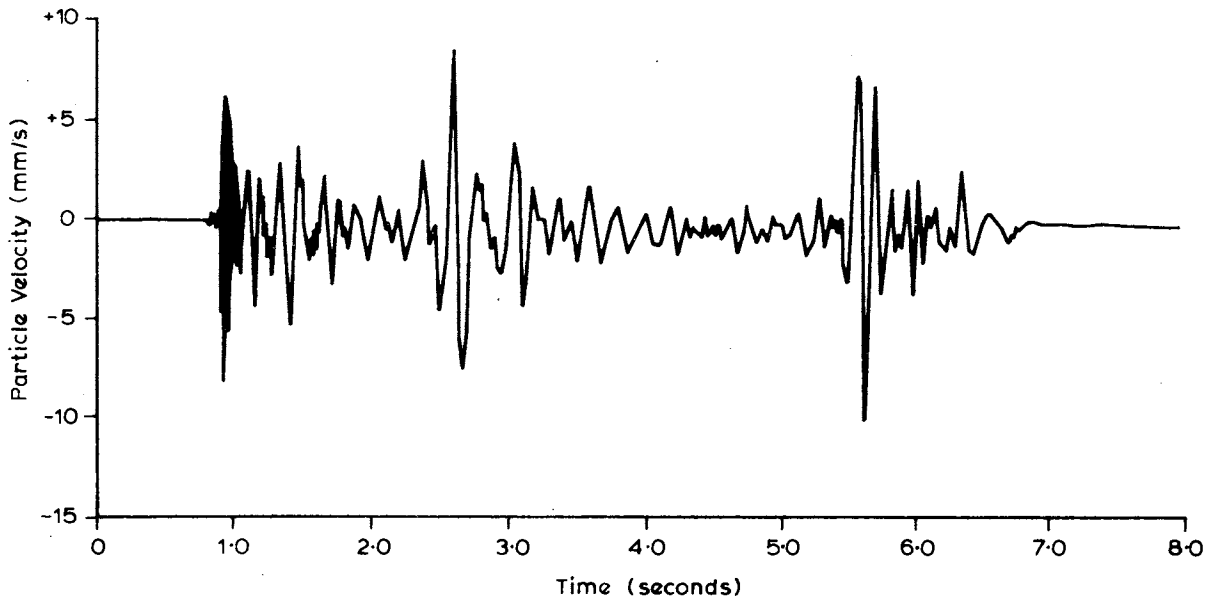


Fig.3. Vertical ground motion 30 m from a collapsing cooling tower

position shown on Fig. 1.

14. Because of the planning that had gone into the field programme the analysis of the data to achieve the required objectives was relatively straightforward. Discussion will therefore be limited to one aspect that can provide a lesson for future similar studies. This is the significance of the local geology at a ground vibration recording station. In Fig. 2 are plotted the peak vector vibration levels against scaled distance for the quarry blasts. Scaled distance here is defined in accordance with normal practice by $D/W_T^{0.35}$ where D is the blast-detector separation and W_T is the total charge. The line drawn on Fig. 2 is a regression one based only on the data from the measuring positions on the glacial drift. It may be seen that this line forms an upper bound to the data from the rock positions. This indicates a rock to drift vibration "magnification" factor which comparison of the data from paired detectors shows to vary between $x 2$ and $x 3$.

La Collette

15. La Collette is a bay on the eastern edge of St. Helier, Jersey where land is being reclaimed and a deep water harbour being built. A necessary part of the harbour construction is the removal of an average of 5 metres of the local granite over an area of approximately 100 m by 200 m about 400 m offshore. Usually with a blasting exercise of this nature the restraint on charge size is simply associated with the safety of personnel and vessels. As these are easily met and the cost of explosives is small compared to a second drill and blast operation then the tendency is to overcharge. At this site however the closeness of the island's main electricity generating station with associated protective relays and six liquid petroleum gas storage tanks precluded this approach. The problem therefore was to ascertain a charge size that would allow economic removal of the rock but not give rise to vibration levels that could endanger the safe operation of the two plants.

16. As it was considered that the electrical relays were the most sensitive items the approach adopted was to determine a site vibration attenuation law by measurements made during a series of small charges and to combine this with selected limiting vibration criteria for the relays to arrive at an acceptable charge size. The attenuation law measurements involved four charges of up to 9 kg being detonated at the depth proposed for blasting in holes drilled as near as possible to the site. Measurements were made with triaxial packs of low frequency geophones and accelerometers spaced on a line between the charges and the power station at positions where the rock outcropped above water level and on other relevant structures about the site. The data from the blasts was plotted on a log-log scale of peak vector vibration level against scaled distance as

defined previously in this paper. A least squares linear regression was carried out on the data and the 95% confidence upper bound line used in the analysis in order to provide a statistical safety factor.

17. For the relays on acceptable transient vibration level was determined from available data (ref. 1). However as the relays were housed in cabinets on the first floor of the power station it was considered necessary to allow for any vibration magnification between the cabinets and the floor and between ground level and the first floor. This was done by monitoring at these points during the trial blasts and also during a series of tests in which small weights were dropped in front of the relay cabinets. These measurements showed magnification factors of $x 1$ for ground to first floor and $x 5$ for floor to cabinets to be applicable. The resultant acceptable ground vibration level taking account of these factors was therefore determined to be 5 mm/s which meant that at the closest point an acceptable charge of 170 kg.

18. At the LPG tanks prior environmental measurements showed a magnification factor of $x 10$ in the horizontal radial mode (with respect to the blast direction) to be applicable. Using the accepted charge level this lead to an estimated peak vibration level of 50 mm/s and a displacement of 0.8 mm on the flanges; levels considered to be acceptable in view of the good condition of the pipework.

19. During the rock blasting programme, which still continues, two long term automatic monitoring units have been installed in order to check that the determined acceptable levels are not exceeded. These units are 4 channel peak level recording systems designed and built by Soil Mechanics Ltd to give 30 days recording on pressure sensitive paper and having switchable full scale ranges of 0.5 mm/s to 100 mm/s. The geophone sensors are located on items that are felt to be particularly sensitive to vibrations so that during blasting operations a check can be made to ensure that the specified criteria are being adhered to.

20. To date the limits have been exceeded on two occasions; once when sympathetic detonation of two series of charges occurred and once, inexplicably, with a charge of only 35 kg.

Cooling towers

21. Throughout the country many first generation power stations are coming to the end of their useful working life and together with their associated cooling towers are being demolished. Because of the substantial financial saving and a need to minimise hazard to demolition operatives serious consideration is always given nowadays to collapsing the cooling towers by the use of controlled explosive charges. In assessing the feasibility of this approach consideration is given to any structures and services in the power

station that are not to be made redundant, and the effect on adjoining property and services. After the risk due to debris or ejecta from the charges in the legs and the shell the next most important cause for concern is usually the possibility of damage resulting from vibrations set up during the collapse. As a result of extensive monitoring operations during the first few cooling tower demolitions it is known that most of the energy is in the frequency range 5 to 30 Hz and the vibrations last for about 10 seconds. (Fig. 3). From attenuation information gathered at these early demolitions it is also possible to estimate with reasonable accuracy the likely magnitude of the vibration levels produced by a given tower and associated ground conditions (ref. 2).

22. Vibration monitoring during a demolition therefore is nowadays usually as an "insurance policy" against unwarranted claims for compensation and not to obtain data for detailed analysis, although occasionally special circumstances arise where ground conditions are not covered by previous experience. As such the requirements of a monitoring system are that it will give a faithful record of the ground motion,

preferably in terms of particle velocity, (which is commonly accepted as being closely related to environmental damage), will give an on-site visual record, is easily moved to site and is quick to install. The ideal practical choice for such monitoring exercises are low frequency geophones connected to an ultra-violet recorder. However when it is expected that it is required to study in detail the response of some structure or component then the use of the tape recorder based system becomes obligatory.

ACKNOWLEDGEMENTS

23. The authors gratefully acknowledge permission of the South of Scotland Electricity Board and the Ports of Jersey to present data and the permission of the Directors of Soil Mechanics Limited to publish this paper.

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Discussion on Papers 9 and 10

DR P.L. WILLMORE (Institute of Geological Sciences, Edinburgh): Is there any specification for the sand used for packing-in instruments?

MR BUCKLEY (Paper 10): Ordinary builders' sand is quite acceptable. You want a material which packs well - not a loose sand.

MR G.A. FOSTER (Vibra-Tech Engineers, Inc., Rockville, Maryland, USA): The use of smaller portable field seismographs, such as our own Vibra-Tape, would allow the completion of a study such as those described by Mr Buckley at less cost and with the use of lower calibre field personnel.

Most US authors, including the US Bureau of Mines, use a square root scaling relationship rather than a cube root one as used in Paper 10 (Fig.2). Cube root scaling can be justified by dimensional analysis only if a spherical explosive charge is used. Since all charges are cylindrical, square root scaling is justified. In practice, using either method makes very little real difference to the data interpretation.

MR BUCKLEY: It is the authors' opinion that there is a fundamental difference in the vibrations monitoring market in the USA and the UK which inevitably is reflected in the equipment appropriate to each. In the former, where there is compulsory monitoring of most quarrying, there is obviously a market for the routine service provided by Mr Foster. In the UK this market is, at present, relatively small, and to be commercially viable depends to a large extent on being able to undertake more complex 'one-off' exercises; hence the authors' choice of instrumentation that allows for versatility.

Regarding scaling laws, there is strong theoretical support for applying a cube root relationship to all contained charges. However, our experience, as Mr Foster's, is that in most cases use of either only marginally affects the data interpretation.

MR E. SIVAPALAN (Trent Polytechnic, Nottingham): Mr Buckley used an 'epoxy resin mounting technique' to measure the response of a concrete floor. How confident is he in saying that these measurements give the actual response of the floor?

How does a change in the mass ratio or the area of contact of the base plate on which the sensors are mounted affect the measurements made on the soil surface?

MR BUCKLEY: The authors have not done any tests involving casting a sensor within a concrete floor, so they cannot be categorical on this matter. However, in view of the small dimensions and mass of a sensor it would be surprising if the sensor did not give the floor response.

The effect of a change in mass ratio of a sensor mounted on the surface of the soil is discussed by Dr Skipp in Paper 2.

DR B.O. SKIPP (Soil Mechanics Ltd, Bracknell): I have found that typical sensors when buried about 300 mm below the ground surface give a response similar to that of a device mounted on a 300 mm dia. aluminium disc on the ground surface and having a very low mass ratio, less than two.

DR R.H. HELMY (The City University, London): Mr Foster has mentioned that cube root scaling is no longer applied and that square root scaling is more relevant, except with spherical charges. However, cube root scaling is generally quite acceptable, and the various scaling formulae used in different techniques do not suggest that square root scaling is much favoured. I would, therefore, prefer cube root scaling so long as no particular rule has yet been accurately established.

Did Mr Buckley try to correlate between the soil parameters or physical properties and the soil's response to vibration by blasting? Such correlation would be of considerable help to further research on the subject.

MR BUCKLEY: We have made no attempt to carry out a correlation of the form suggested.

MR M.J. BALL (Nobels Explosives Co. Ltd, Ponteland, Newcastle-upon-Tyne): Paper 10 gives a very interesting insight into how careful monitoring of blasts and the interpretation of data can go a long way in ensuring that future operations are conducted without giving rise to excessive vibration emissions.

However, the instrumentation used for such field exercises is perhaps somewhat over-sophisticated, and, as Mr O'Neill remarked earlier, the field blasting vibration engineer needs a system whereby the peak particle velocity or some other measure, together with a frequency, is readily obtained to allow a virtual on-the-spot decision to be made, and I wonder if the authors are perhaps over-instrumenting.

Secondly, the regression analysis carried out

at one of the sites makes reference to total charge and not charge per delay. It has long been recognized that splitting the blast up into a series of smaller blasts by short delay detonators reduces vibration intensity, and indeed this system forms the basis of short delay firing. I therefore wonder if the authors are correct in their assumption of plotting peak particle velocity against the cube root of W_T , where W_T is the total charge. This could well account for the lack of correlation in their results. Our own company similarly carried out a regression study at this same site and reached a much better degree of correlation on hard rock by using the square root of W per delay.

The whole concept of delay firing is widely used in most countries and does reduce vibrations, no matter what the distance involved. Consider the case of an explosion in our explosives works, which was recorded by the seismic station at Eskdalemuir, 100 km away. This revealed not one, but two blasts separated by 10 ms. A subsequent investigation revealed that there had been two explosions, showing the effect of delays at this great distance.

MR BUCKLEY: As part of a commercial organization, the authors are only too well aware that the degree of sophistication in a particular monitoring exercise must be related to the purpose for which the data is being collected. This is why the authors have opted for an instrumentation system that can cope with simple measurements (based on the UV recorder) and large extensive studies (based on the multi-channel tape recorder). If a substantial part of the authors' work was similar to that of Mr Ball (i.e., check monitoring on quarry blasts) then without doubt they would use a portable unit specifically designed for this limited range of use.

Regarding the use of delays, care must be taken to distinguish between those cases involving small charges and short distances and those with larger charges over longer ranges. Also, the capability to distinguish by advanced correlation techniques two events separated by a few milliseconds must not be taken to mean that they are two separate events from the magnitude aspect. With the low frequencies that predominate at large distances this is clearly not so. It is the authors' experience from several sites that at ranges of greater than a few hundred metres the use of short (millisecond) delays does not significantly reduce ground vibrations from larger charges.

As for the use of weight per delay, the data from Torness to which Mr Ball is referring was also plotted against this quantity but showed no better degree of correlation.

The difference between our findings and those of Mr Ball is probably explicable in terms of the much shorter ranges that we understand Mr Ball's measurements to have been made over.

MR D.B. O'NEILL (Crockett and Associate, Carshalton): In my experience, the use of epoxy resin to fix an array of transducers to, say, a concrete surface is completely satisfactory.

When delay detonators are used in blasting, the charge weight ought to be specified as the

'maximum instantaneous weight'. For millisecond delays, the instantaneous weight may be that of two or even three delayed charges due to co-operation, but for long half-second delays the charge weight should be that of individual holes.

I should like to ask Dr Wootton if the technique of structural monitoring has been based on methods previously developed for other purposes and, conversely, can he foresee the technique being applied to other structural systems; e.g., testing buildings after earthquake or settlement.

DR WOOTTON (Paper 9): Mr O'Neill raises an interesting point and perhaps when we have had experience with offshore structures we may be able to monitor other buildings and study if they have been damaged as a result of an earthquake. Experiments on these lines have already been carried out in California.

PROFESSOR D.J. JOHNS (University of Technology, Loughborough): Further to the question by Mr O'Neill, I believe the time is approaching when civil engineers will consider it more normal to instrument buildings for in-service monitoring. In the field of wind excitation, it is known that a newly erected tall building may cause an unacceptable level of vibration in an existing adjacent structure, and the legal implications are obvious. The designers (and owners?) of both structures should perhaps be concerned to do some continuous monitoring just as, to a degree this is done for current civil aircraft types.

Regarding Paper 9 (methods of structural analysis, §3) I would like some further discussion as to why the three lowest modes are of little use. One presumes that the pile modes are of interest in themselves, e.g., in their own integrity, as well as their effect on the rest of the structure.

DR WOOTTON: The problem with monitoring the low modes is that they are susceptible to changes in the weight of the deck structure caused by drilling operations and other load changes. In practice, movement can probably be detected by changes in the static geometry of the structure.

DR P.J. BRAMAH (United Kingdom Atomic Energy Authority, Springfields): Would Dr Wootton please explain why the natural frequencies of his structures are changed by wave direction and whether cracks, rather than large-scale failures, can be detected by his techniques.

The aircraft industry has long used the technique of adding mass to determine stiffness from resonance tests. This is the reciprocal of the technique that he is using.

DR WOOTTON: The dynamically effective mass of an offshore structure comprises two components: the mass of the structure and the added mass of the water. The latter is not constant but varies according to the direction of oscillation relative to the water and there is a small effect which depends upon water motion direction. More particularly, the various wave directions excite different modes and when each member

shows a change of stiffness, wave direction produces the additional clue.

DR C.D.V. WILSON (Liverpool University): Mr Buckley, when your instruments are mounted on bed-rock, does the reverberation of the steel mounting cause any complications?

MR BUCKLEY: The authors did not experience any spurious vibrations that could be associated with the steel mounting rods. It must be stated that this mounting and the additional work it involved was for a specific reason; i.e., to avoid coupling only to the possibly weathered surface layer of the rock. In general, a satisfactory coupling of the sensors is achieved by the use of epoxy resin.

DR P. SRINIVASULU (Structural Engineering Research Centre, Adayar, Madras, India): Dr Wootton has mentioned about the added mass effect of water in tracing small changes in frequency and thereby inferring the location and extent of any damage in the structure. At the same time, he has not mentioned about the presence of water in the model study he refers to in the paper. Would he elaborate on this point?

Is there any practical evidence to convince oneself of the desirability of comparing the peaks in the frequency domain before and after the occurrence of a damaging event, such a comparison leading to a realistic guess on the location and extent of damage?

Have any vibration records been obtained at the base of an offshore platform now existing? If this data is available, is it not a better and more direct approach to study the structural response by testing a dynamically similar model on a shaking table with the prescribed base motion given to the table?

DR WOOTTON: The model shown in Fig.4 of the paper was tested in air in order to provide the various systems. Full-scale results are presently being acquired from real offshore structures. The second point concerns the change in the frequency which we had carried out before and after the failure and the change in damping which results in changes in the magnitudes of the peaks. In practice, it is difficult to measure this change of damping accurately. We have not used the shaking table of the form used in earthquake analysis, but rather excitation models mounted to earth by external shakes. No vibration results have been obtained at the bottom of offshore platforms as far as the author is aware.

MR C.R. TURLEY (Northern Explosive Services Ltd, Leeds): Would Mr Buckley comment on the view that the prediction and analysis of man-made vibrations is an inexact science (rather like explosives engineering) and that the range of damage on structures and services is so wide that effects can only be predicted or assessed by a person with wide experience in this field.

If this is so, it is the responsibility of the Institution of Civil Engineers to say so to the civil engineer, so that he does not use a rubber stamp in the specification of every contract saying that a certain figure is not to be

exceeded.

MR BUCKLEY: I think that this is a question best directed at one of the speakers later today.

DR ASHLEY (Paper 16): The ISO draft amendment discussed in my paper is an attempt to bring guidance into a difficult area. It is always unsatisfactory to specify a single figure limit or to apply such limits without specific reference to the circumstances and applicability. Nevertheless, it is better to have a document which can be used as guidance on an international basis rather than to depend on the expertise, which may conflict, of a range of consultants.

As far as construction work is concerned and the effect of vibration, what is now required is a British Standard or Code of Practice, which could incorporate the international recommendations and yet is usable and understandable by the industry. In the preparation of such a document, all sides should be fully represented.

MR J.J. CLEETON (ECC Quarries Ltd, Leicester): Has Mr Buckley any experience of a site where an artificial interface, such as that caused by a pre-split operation, was introduced between a quarrying operation and private property in order to create a free face from which the vibrations caused by blasting might be reflected, thus reducing vibration at the private property?

When vibration recordings are being undertaken in expensive private properties, can the author suggest the most suitable type of coupling that is satisfactory, both for the quality of the reading and to ensure minimum disruption to the owners of the property.

MR BUCKLEY: The authors have no experience of this situation. However, on theoretical grounds, based on the wavelength of the vibrations it would be expected that such a free face would have to be of substantial dimensions to be effective.

Regarding mounting of sensors, the essential requirement is for a rigid coupling that does not produce magnification. This can either be by bonding with epoxy resin or the use of a clamping device. With care, inconvenience to the owner and damage to property can be negligible.

MR L. KENNY: (Institute for Industrial Research and Standards, Dublin): When monitoring vibration on offshore structures, which parameter is of more importance - statistical accuracy of vibration amplitude, or resolution of vibration frequency?

DR WOOTTON: Mr Kenny raises an interesting point to do with the stationality of the data. If a large result is analysed then the resolution is marred by small changes that occur in the frequencies. It simply becomes a matter of judgement to select the right results, and experience on field data is the only way to obtain the method for judging.

11. Analysis and correction of ground and structure motion recordings

K.G. MEDEARIS, PhD and J. WILSON, PhD (Kenneth Medearis Associates (KMA), Fort Collins, USA)

The importance of properly correcting ground and structure motion recordings to eliminate low frequency drift and high frequency noise cannot be overemphasized. Analytical results based on uncorrected record data are often significantly in error. Unfortunately, a number of these have even been included in published works. This treatise describes a record correction procedure which, coupled with good structural dynamics judgement, proved to be of significant value in a recent seismic response research effort.

INTRODUCTION

1. The catastrophic effects of earthquakes such as Anchorage, San Fernando, and Managua are well known. The prevention of loss of life and damage due to earthquakes is of significant importance, and the subject of continuing research efforts throughout the United States and other countries. In this regard, it is clearly important to obtain information concerning the response of full-scale structures to dynamic loadings. Noting the ground motions produced by an underground nuclear detonation are quite similar to those generated by an earthquake, Kenneth Medearis Associates(KMA) was able to take advantage of a recent U.S. Atomic Energy Commission Plowshare Project to study the dynamic response of actual structures.

2. Project Rio Blanco was the third underground nuclear gas stimulation experiment to be conducted in the United States. It involved the detonation of 3 - 30 kiloton nuclear devices more than 1.6 kilometers below ground level in Rio Blanco County, Colorado, on May 17, 1973. The Project sponsors were CER Geonuclear Corp., Las Vegas, Nevada, Equity Oil Co., Salt Lake City, Utah, and the Atomic Energy Commission(AEC). Kenneth Medearis Associates(KMA), a Colorado research and engineering firm, was the structural response and slope stability consultant for the Project.

3. A dynamic response research study of full-scale structures was also conducted by KMA under the sponsorship of the National Science Foundation(NSF) and the American Society of Civil Engineers(ASCE). Five Rio Blanco area structures were selected for instrumentation and theoretical analyses. These were located between 6.4 and 64 kilometers from the detonation point, and experienced peak base accelerations of 0.003 - 1.0 g's. They included the 31 meter high, truss-type, White River Electric microwave tower, the 22 m vertical, cylindrical steel, Chadbourne Corp. depropanizer, the 1-story wood Rock School residence, the 25 m clear span, wood roof, reinforced-concrete column, Rangely College gymnas-

ium, and the 25 m high Harvey Gap earth-fill dam. All had previously been dynamically analyzed as part of the structural response effort. L-7 seismic recorders were installed at the base of, and on, each of the structures to monitor their responses to the detonation ground motions. The L-7 system is a compact three-component velocity seismograph, which records on a five-day tape recorder. It has a flat velocity response over a frequency spectrum of about 0.3 - 25 Hz. The system is available in 3, 6, and 12 channels, and has the capability for field calibration of the seismometers, amplifiers, tape recorders, and power supply. A total of 43 seismometers were installed, 41 of these recording satisfactorily during the detonation.

4. The analog velocity records obtained during the detonation were subsequently processed by another organization, the digitized values being provided to KMA on magnetic tape. These values proved to be unusable since no corrections had been utilized. A second set of digitized records, incorporating some baseline corrections, was requested and provided.

Record correction procedure and results

5. Double integration of the second set of digitized records gave displacement time-histories with large amplitude, long period components, the magnitudes of which were obviously incorrect. A parabolic baseline correction (ref. 1) was then applied to several of the acceleration records but the resulting displacements were still unrealistic. It was concluded that additional correction to remove certain low-frequency components was mandatory. A review of numerous references revealed that much work remains to be done with regard to record correction. Indeed, a number of published displacement records appear to be in error.

6. Although not an anticipated part of this research, a satisfactory record correction and computer routine were developed in order to carry out the dynamic analysis effort. Basically, the procedure digitally filters low-frequency comp-

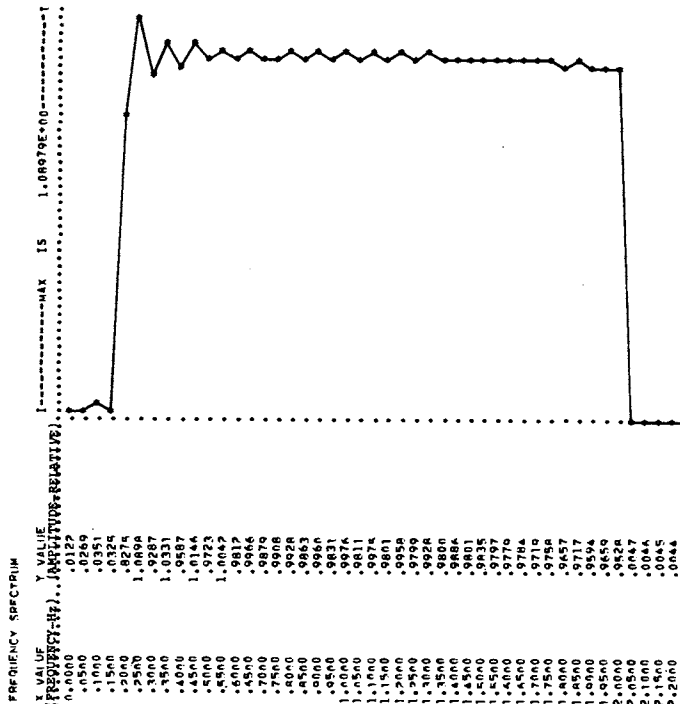


Fig. 1. Test function Fourier spectrum - filtered data

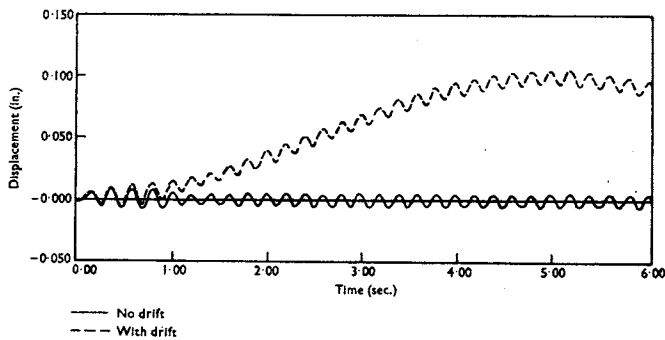


Fig. 2. Test function displacement response uncorrected data

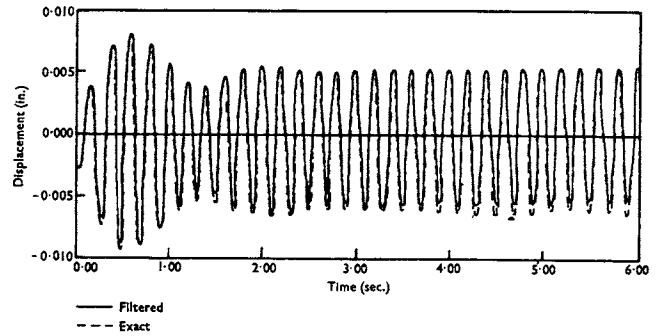


Fig. 3. Test function displacement response - corrected data

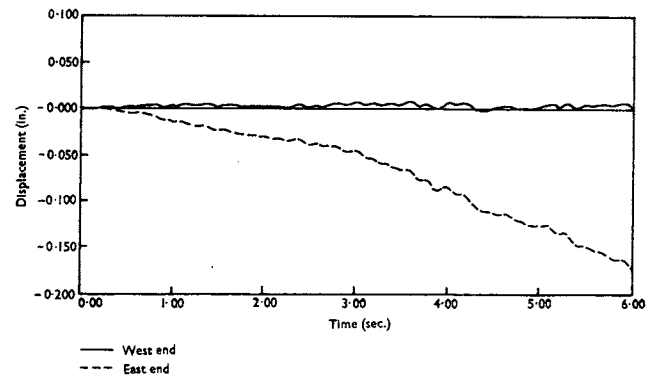


Fig. 4. Rangely College transverse responses at base - uncorrected data

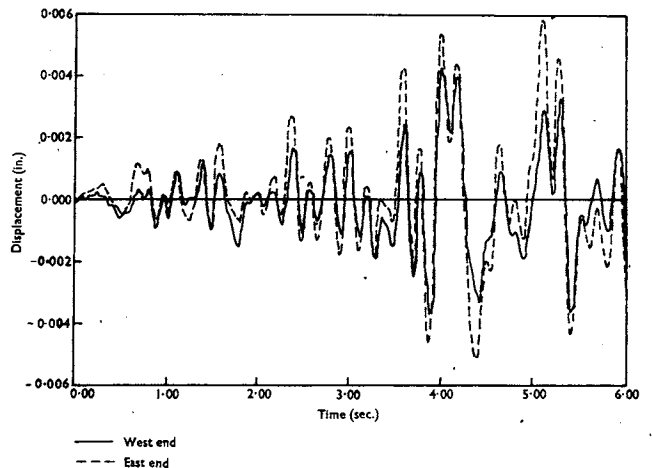


Fig. 5. Rangely College transverse response at base - corrected data

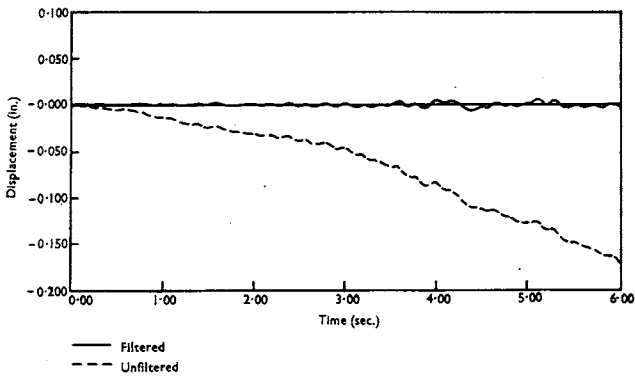


Fig. 6. Rangely College transverse response at base - corrected and uncorrected data

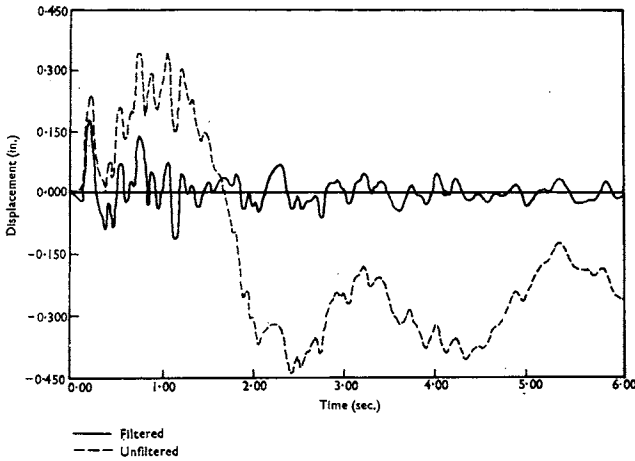


Fig. 7. White River tower radial response at base corrected and uncorrected data

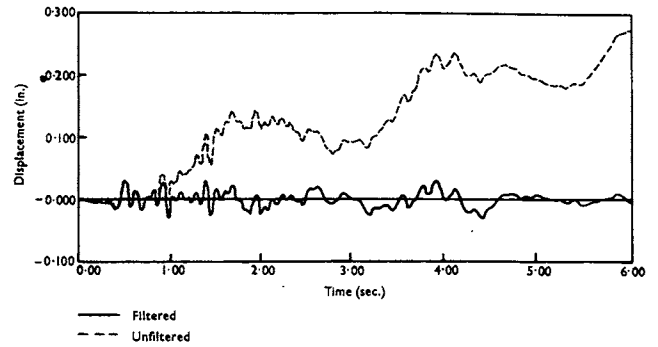


Fig. 8. Rock School residence radial response at base - corrected and uncorrected data

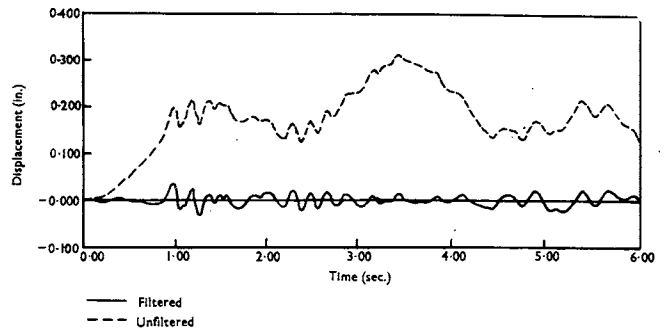


Fig. 9. Chadbourne depropanizer transverse response at base - corrected and uncorrected data

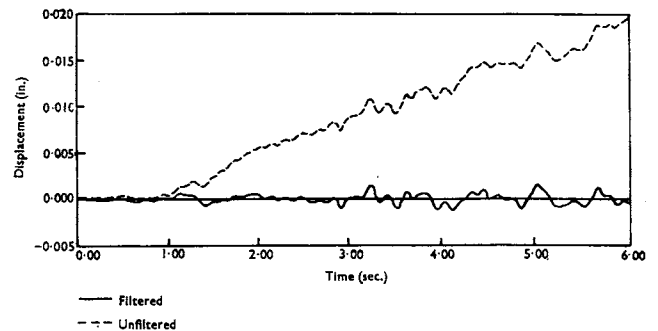


Fig. 10. Harvey Gap dam transverse response at base - corrected and uncorrected data

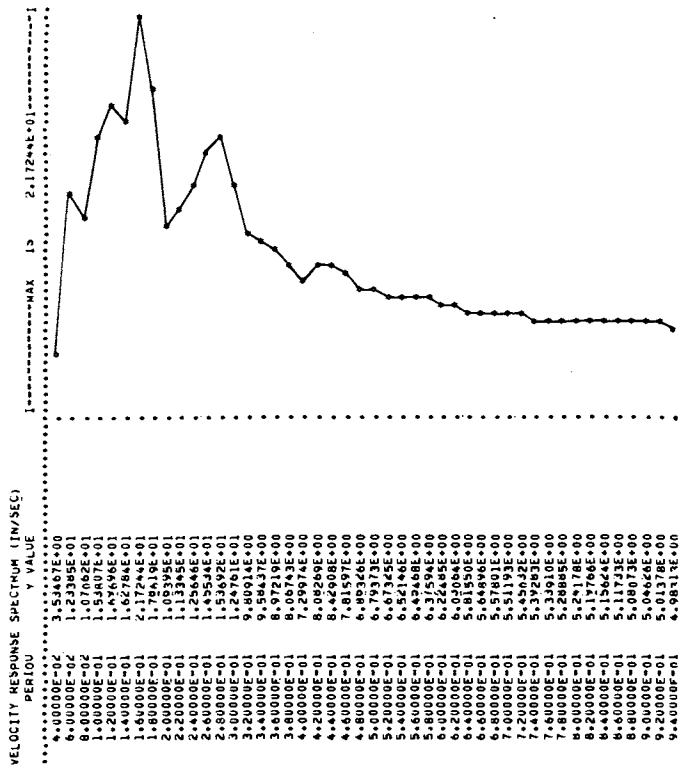


Fig.11. White River tower radial ground motion spectra - 2% damping and uncorrected data

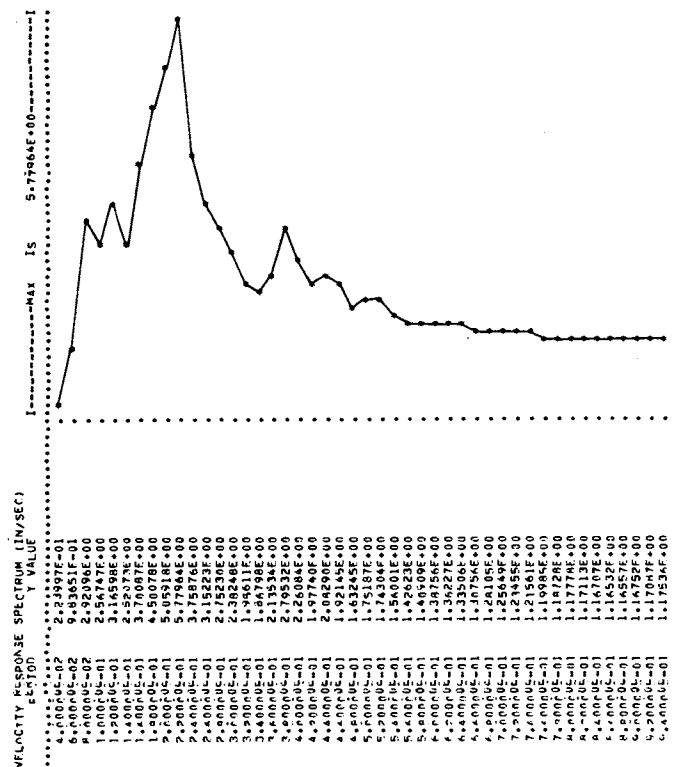


Fig.13. Chadbourne depropanizer transverse ground motion spectra - 2% damping and uncorrected data

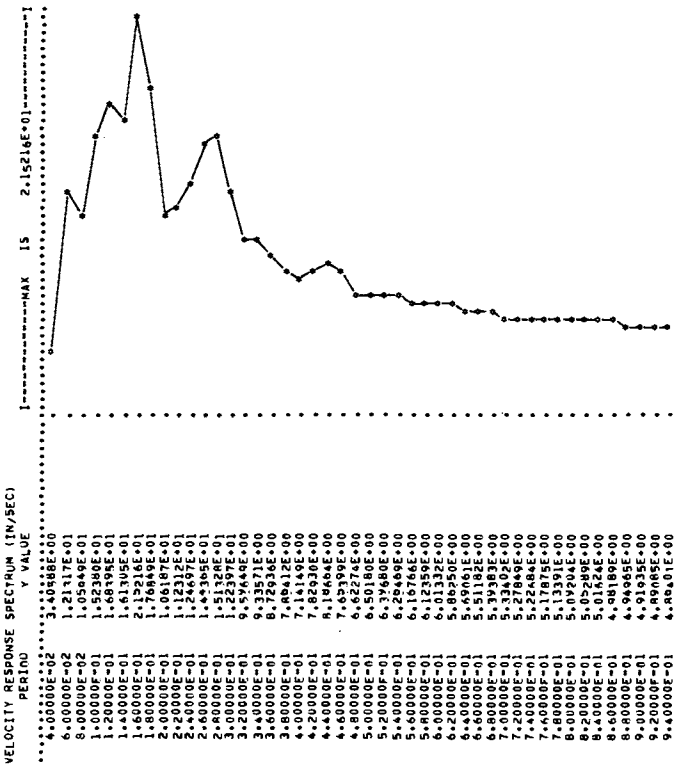


Fig.12. White River tower radial ground motion spectra - 2% damping and corrected data

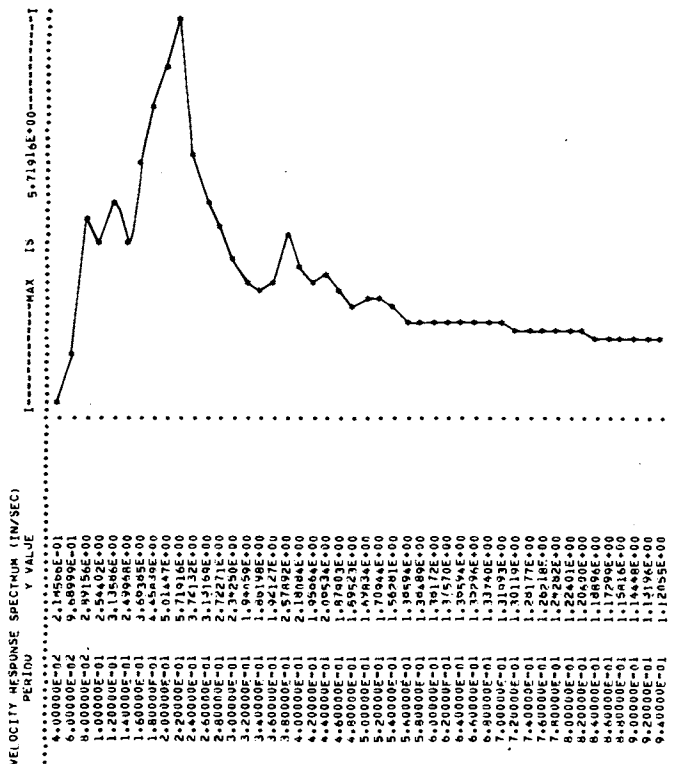


Fig.14. Chadbourne depropanizer transverse ground motion spectra - 2% damping and corrected data

onents, the first step being to integrate the uncorrected accelerations to obtain velocities. A running mean filter is then applied to these velocities to obtain a reduced record of lower frequency components. The reduced record is then fit in the least-squares sense (ref. 2) with a polynomial whose order is determined by the cut-off frequency desired. The polynomial approximation is subsequently interpolated to regain the original number of data points, and then subtracted from the original velocity record. The resulting corrected velocity record is numerically differentiated to obtain the corrected acceleration record. Displacements obtained by either single integration of the corrected velocity record or double integration of the corrected acceleration record were then found to exhibit substantial agreement. In most cases, the running mean filter employs a 9 point smoothing formula, thus reducing the number of points to be least-square fitted by a factor of 9. The largest cut-off frequency utilized was 0.85 Hz. The order, n , of the least-square fit polynomial is determined by the equation:

$$n = 1 + 2 f T \quad (1)$$

where f is the cut-off frequency in Hz and T is the record length in seconds. An 18th order polynomial is thus required for an 0.85 Hz cutoff frequency and a 10 second record.

7. The effects of utilizing the correction on a test function containing all components of $\cos(2\pi i t/20)$, $i = 0, 1, 2, 3, \dots, 40$, is given in Fig. 1. This function was filtered using a cut-off frequency of 0.25 Hz, and Fig. 1 shows the Fourier frequency spectrum of the filtered data. It may be noted the unfiltered data have coefficients of unity for frequencies from 0 - 2 Hz and zero otherwise.

8. The effects of the correction process on acceleration and velocity data was small, but peak displacements were, in some cases, changed by an order of magnitude. To demonstrate the process, a test problem was solved using parameters relevant to one of the instrumented structures, namely the Rangely College Gymnasium. That structure is predominantly a single degree-of-freedom system, for which a damping value of 5% of critical is appropriate. The dominant frequency of the recorded ground motion at the site was about 5 Hz, with an acceleration peak on the order of 5.1 cm/sec^2 . For the test case, a long period drift component of $0.051 \cos(.2\pi t) \text{ cm/sec}^2$ was superposed on a theoretical ground motion of $5.1 \cos(10\pi t) \text{ cm/sec}^2$. The exact displacement response for this ground motion, with and without the drift component, were calculated and are plotted in Fig. 2. It may be noted the drift component amplitude is only 1% of that of the theoretical ground acceleration, yet it causes several hundred % error in the peak displacement response. Such an effect may easily be introduced in records as a result of mechanical drift in the recording device or errors in the digitization of the analog records. The theoretical ground motion, with drift superimposed, was then digitally filtered and the

displacement response calculated. That solution is plotted in Fig. 3 along with the exact response to the ground motion excluding the drift component. The close agreement is readily apparent.

9. Drift in certain records was easily ascertained. For example, the Rangely College gymnasium has an axis of symmetry in plan. Seismic units were located near the East and West ends of the floor and roof, and aligned with the axis of symmetry. Six seconds of displacement time-history were obtained by integrating the digitized records taken on the floor, with and without low-frequency filtering. The seismic units were located about 23 m apart on an in-plane rigid concrete slab, suggesting that close agreement between the displacement records could be expected. The obtained results are plotted in Figs. 4 and 5. It may be noted the displacement time-histories given in Fig. 4 indicate an unrealistic rotation of the structure foundation. The results obtained using filtered records are depicted in Fig. 5, essentially agreeing in form, although the east end (nearer the detonation) has larger amplitude.

10. Six seconds of integrated ground displacements for each instrumented site, with and without filtering, are plotted in Figs. 6 through 10. It may be noted the displacements obtained using unfiltered data increase unrealistically to large values with time.

11. Velocity response spectra for 2% damping were computed using filtered and unfiltered data from two sites, the White River Tower and the Chadbourne depropanizer. These are plotted in Figs. 11 through 14. The correction procedure typically decreased the displacement response for periods in the vicinity of 1 second, while velocity and acceleration responses were essentially unchanged. The spectra generated using the original data had large long period components, primarily resulting from baseline errors.

12. This treatise has dealt with the record correction phase of a research effort which has provided valuable insight concerning the response of full-scale structures to seismic motions. A detailed description of that research effort is given in ref. 3. It is hoped the results presented herein will create more awareness of the absolute necessity of properly correcting seismic motion recordings.

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12. Contributions of early instrumental seismic recordings to engineering analysis

D. PASTAMATIIOU, PhD (Dames and Moore, London)

Invaluable information on the near field of old large earthquakes may be extracted from early far field seismic recordings. This information is unique, since earthquakes of this size have not been repeated within the period of instrumental seismology.

INTRODUCTION

Earthquake engineering is primarily related to near field seismology since most of the destruction potential of a shallow earthquake is in the epicentral area.

Near field seismology has benefited from the description of seismic sources as physical rather than geometric point sources. However, serious limitations to the engineering applications of the recent advances in near field theoretical seismology are posed by the lack of near field measurements. These measurements are expensive to obtain due to difficulties in predicting earthquakes in space and time as well as the short duration and the small geographic coverage of the generated strong ground motion. On the other hand far field measurements of recent earthquakes are obtainable by sensitive instruments at large epicentral distances. Therefore, one can learn about the near field, where measurements are scarce or do not exist, by extrapolating far field measurements through theoretical considerations. This extrapolation reveals only overall near field characteristics that can be seen from far away. The above methodology can be checked in cases where good near field data are available. These test cases are bound to be in high seismicity areas, like California, where near field data are cheaper to obtain.

In regional evaluations of expected strong ground motion one is interested to know about the near field characteristics of large earthquakes. Since large earthquakes are rare one would like to see long periods of instrumental measurements. Therefore, in engineering evaluations of ground motion one would like to profit from early seismic recordings of large earthquakes. Early instrumental recordings are of equal help in low as well as high seismicity areas. The two areas differ in the size of the large earthquake e.g. in Scandinavia a large earthquake is the 1904 Oslo earthquake ($M_s = 6.0$) whereas in California a large earthquake is the 1906 San Francisco earthquake ($M_s = 8.3$).

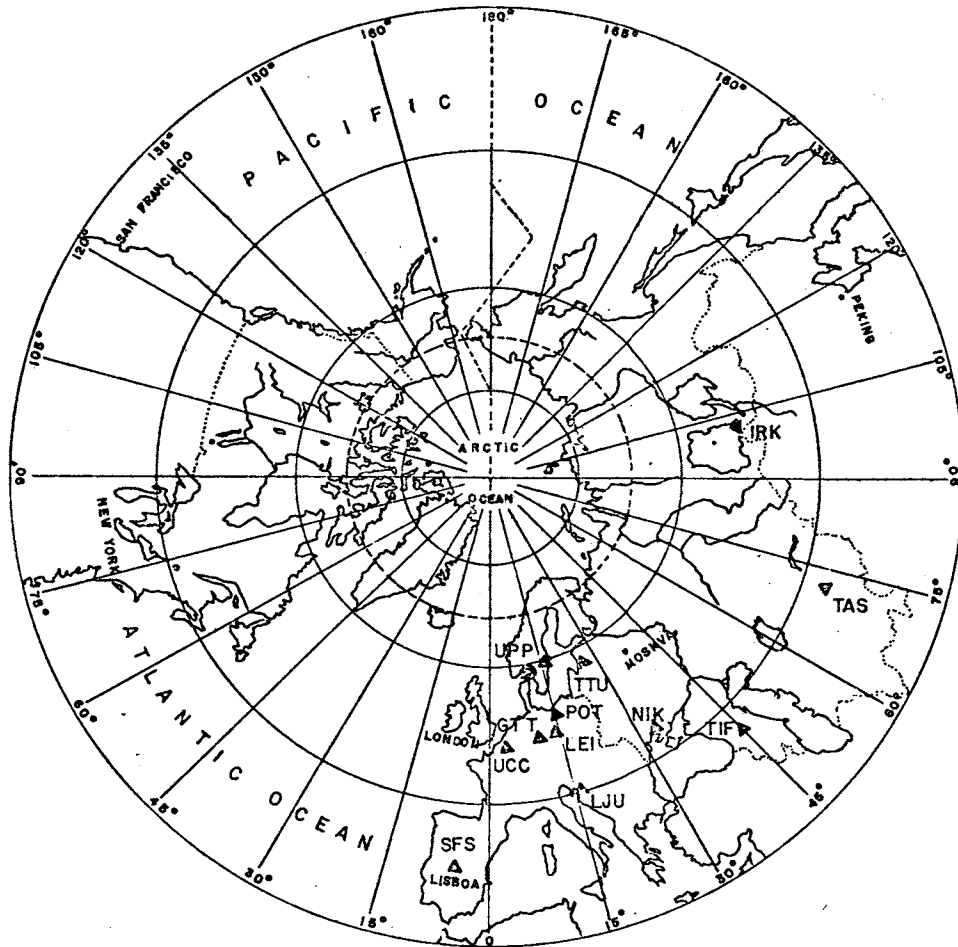
In both cases the same size event has not been repeated within the period of instrumental seismology.

This contribution does not look into new developments in instrumentation. It is mainly concerned with invaluable old recordings of rare seismic events. The potential of such recordings is discussed in more detail and an example is given from the 1904 Oslo earthquake.

EVALUATION OF EARLY INSTRUMENTAL RECORDS

Seismological instruments (recording time history of ground motion) were installed at the turn of the century. However, early instruments had a small radius of perceptibility and were few and non-uniformly distributed. Therefore, early seismic registrations do not offer the large number of measuring stations necessary for accurate epicenter determinations or fault plane solutions. Moreover the number of available early records, obtained or kept mainly in Europe, was further reduced after two devastating world wars.

The few available records were obtained from a variety of instruments. Although some instruments, like the Milne seismograph, formed an early standard world network, most seismic instruments were restricted to relatively small geographical regions. On the other hand, early instruments gave clear traces which for known instrument characteristics may be deconvoluted to give ground motion time-histories. Therefore, the value of early seismic recordings relies on their individual quality rather than their number. The early records contain appreciable information in the time domain which may be extracted by mathematical techniques. The actual amount of information depends on the quality of the individual record and the geographical arrangement of the few recording stations with respect to the earthquake epicenter. This information, in conjunction with source mechanism models will reveal near field features of the earthquake.



	STATION	INSTRUMENT
SFS	SAN FERNANDO	MILLNE
UCC	UCCLE	REBEUR-EHLER
GTT	GÖTTINGEN	WIECHERT
LEI	LEIPZIG	WIECHERT
LJU	LJUBJANA	VICENTINIS
POT	POTSDAM	WIECHERT
N'K	NIKOLAEV	REBEUR - PASCHWITZ
TIF	TIFLIS	REBEUR - EHLER
		MILLNE
TAS	TASHKENT	ZÖLNER - PERSOLD
TTU	TARTU	KANKANI
IRK	IRKUTSK	ZÖLNER - PERSOLD

Fig.1. Stations which recorded the 1904 Oslo earthquake

Earthquake source mechanism models vary in their complexity. They start from the simple one-parameter geometrical model where the source is assumed as a point source with strength described by the magnitude M . A physical model is obtained by assigning a dimension to the source. The model is further complicated by adding a kinematic parameter like the velocity of crack propagation. At the other end of the range of available models one has a complete numerical simulation with realistic material properties on the fault. The latter numerical models are not justified in cases where only far field data are available. In the particular situation encountered with early recordings one is limited by few far field records and the use of simple source models is more appropriate.

The simple two parameter model assumes that a sudden stress drop $\Delta\sigma$ produces an instantaneous average dislocation u over an average dislocation area πr^2 . Then the far-field Fourier amplitude spectrum shows on a log-log plot a constant level Ω_0 at low frequencies, a corner frequency ω_0 and a high frequency spectral asymptote γ . Then (Ref. 1)

$$M_0 = 4\pi r^3 \Omega_0 R / 85 \quad (1)$$

where

C = velocity of wave propagation
and M_0 , the seismic moment, is defined as

$$M_0 = \mu \pi r^2 = \frac{16}{7} \Delta\sigma r^3 \quad (2)$$

where μ = rigidity modulus

The corner frequency is related to the size of the source. On a shear wave spectrum:

$$\omega_{os} = 2.34 \frac{C_s}{r} \quad (3)$$

whereas the corner frequency $\omega_{o,p}$ on a p-wave spectrum is related to ω_{os} through (Ref 2):

$$\frac{\omega_{o,p}}{\omega_{o,s}} = \left(\frac{C_p}{C_s} \right)^{\frac{2}{3}} \quad (4)$$

The high frequency spectral asymptote depends on the pulse discontinuity in the time domain (Ref. 3) and varies from -1 to -3.

The particle velocity at the source is related to the stress drop $\Delta\sigma$ by the radiation formula (Ref. 1)

$$\dot{u} = \frac{\Delta\sigma}{\mu} C_s \quad (5)$$

whereas the strong motion duration of the source is made of two terms. The first term covers the rate at which energy is released along the fault whereas the second term accounts for the rate at which energy is released at a point on the fault:

$$D = \frac{L}{V} + \tau_{\max} \quad (6)$$

where V = velocity of fracture propagation

In this formula $L = r$ for bilateral and $L = 2r$ for unilateral fracture propagation.

For the two parameter model (Ref. 4):

$$\tau_{\max} = \frac{24}{7\pi} \frac{r}{C_s} \quad (7)$$

Seismological instruments designed for source mechanism studies should cover the frequency range around the expected corner frequency f_0 . This range should be broad enough to depict the low frequency constant level Ω_0 as well as the high frequency spectral asymptote. We shall see in the next section that with respect to the 1904 Oslo earthquake the old Wiechert instrument had a better design than modern instruments.

AN EXAMPLE

The 1904 Oslo earthquake shook an area of about 500km radius around Oslofjord and was registered by few instruments in Europe. Since no centralising body for seismic information existed at that time, this information was compiled from station bulletins. Few stations were operational in Europe in October 1904. The ones where the Oslofjord earthquake was found recorded are shown on Fig. 1 together with the type of the recording instrument. The nearest one at Uppsala gave a clear trace of P-wave and was thrown off-scale when the S-wave arrived. For all these stations maximum trace amplitude and occasionally corresponding periods were listed. However, a time history was retrieved only from two stations: the near station of Uppsala and the further away station of Leipzig. The former was the actual recording of the P-waves whereas the latter was a reproduction from the station bulletin (the original record survived the first world war but was destroyed in the second). The Leipzig recordings are reproduced on Fig. 2. In both cases the recording instrument was a Wiechert. A description of this instrument may be found in Ref. 5.

The maximum amplitude readings were used for the definition of the one-parameter source model i.e. for the determination of the magnitude of the 1904 earthquake. The calculations followed the layout suggested by Karnik from similar investigations (Ref. 6) and gave a surface magnitude $M_s = 5.9 \pm .3$.

Out of the four available time histories (two horizontal components from each of the two recorded stations) only three were digitised and analysed: the less distorted E-W component from Leipzig and the two components from Uppsala. The Fourier amplitude spectra of the digitised records were interpreted in terms of a two-parameter shear source model. In the computations the following values were assumed: shear wave velocity $c_s = 3.5$ km/sec and P-wave velocity $c_p = 6.5$ km/sec. The results are shown on Table 1.

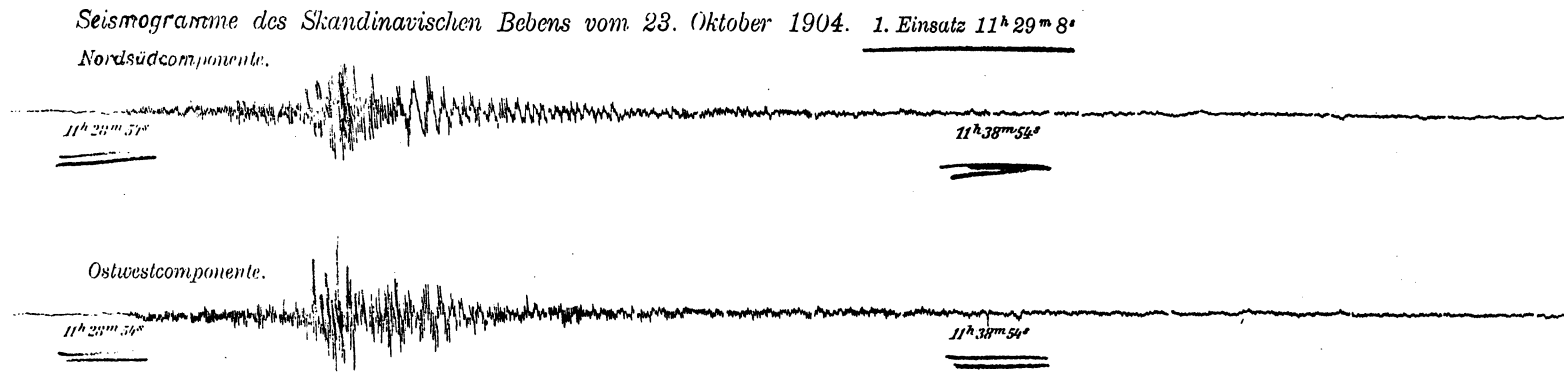


Fig.2. The 1904 earthquake as registered at Leipzig

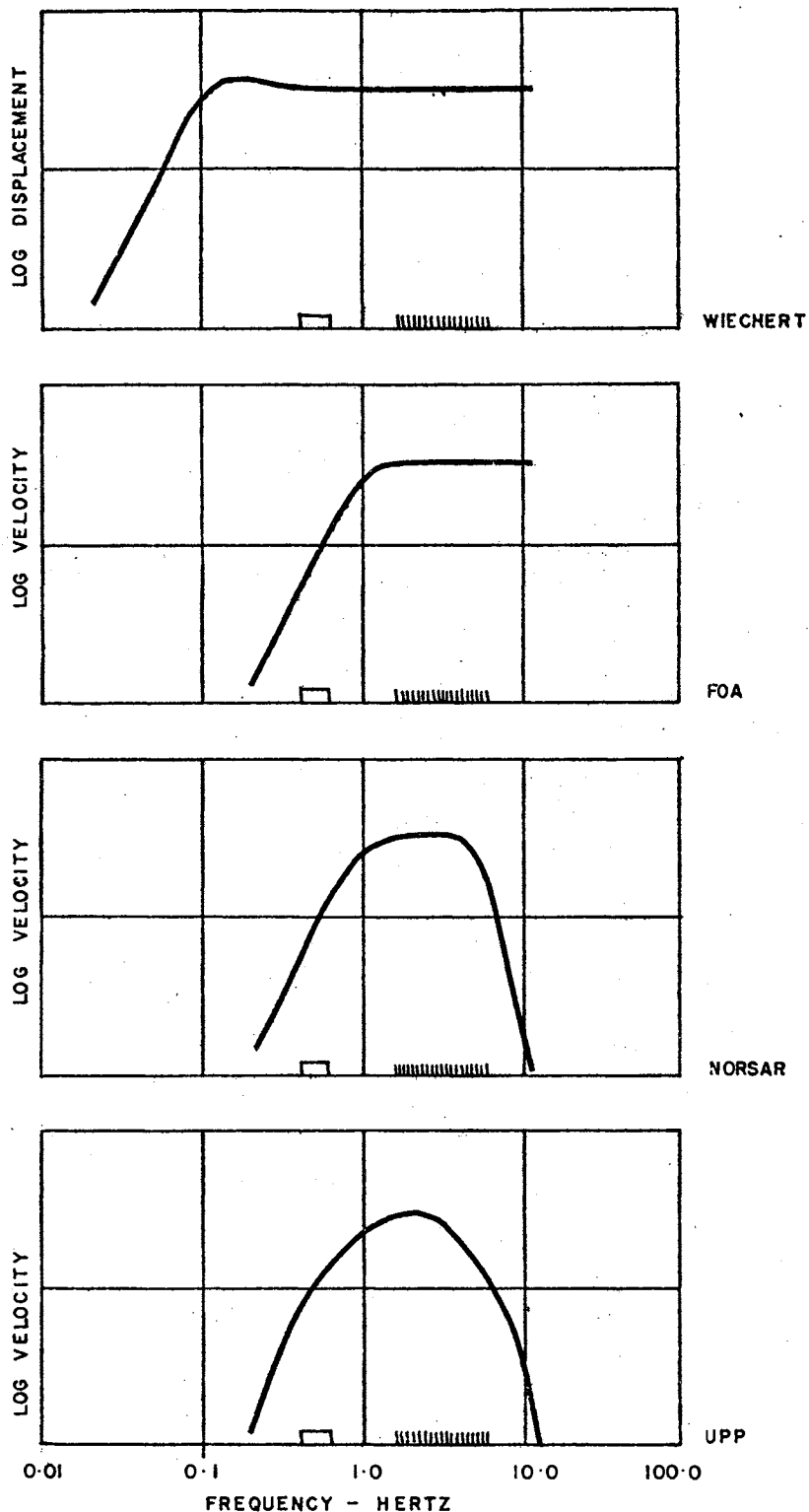


Fig.3. Comparison of seismic instruments operating in Scandinavia (schematic): on the frequency axis are marked the corner frequencies of earthquakes in Scandinavia (|||||| recent small events, □ the 1904 event)

TABLE 1 BASIC SOURCE PARAMETERS OF THE 1904 EARTHQUAKE

STATION	Ω_0	Δ^0	$\Delta(\text{km})$	$\log M_0$	$\log f_{0,s}$	$\log f_{0,p}$
LEI E-W	.52	8.03	899	25.97	-.22	
UPP N-S	.01	3.8	422	24.71	(-.40)	-.22
UPP E-W	.01			24.71	(-.30)	-.10

Further application of the two-parameter shear model gave a range of values for the source dimension and strong motion duration as shown on Table 2. In these calculations the velocity of crack propagation was given the value of 3.5 km/sec of the shear wave velocity.

TABLE 2 DERIVED SOURCE PARAMETERS OF THE 1904 EARTHQUAKE

DISLOCATION RADIUS r (Km)	DISLOCATION SIZE L = 2r (Km)	RISE TIME τ_{max} (sec)	STRONG MOTION DURATION D (sec)
---------------------------	------------------------------	------------------------------	--------------------------------

2.2 to 3.3 4.4 to 6.6 .7 to 1.0 1.3 to 2.9

The stress drop at the source may be obtained from eqn 2. After substitution we obtain the average value:

$$\Delta\sigma = 310 \text{ bars}$$

in agreement with values obtained from other intraplate earthquakes (Ref. 7) This value of $\Delta\sigma$ corresponds, according to eqn 5, to a particle velocity at the source:

$$\dot{u} = 310 \text{ cm/sec}$$

For the focal depths encountered in Scandinavia this value of source particle velocity will be strongly attenuated before it reaches the epicentral region.

Finally it is interesting to compare the response characteristics of the old Wiechert instrument with modern instruments operating in Scandinavia. This comparison is illustrated in Fig 3 where amplification curves are shown

for the different instruments. On the frequency axis are marked the corner frequency range of small recent earthquakes and the corner frequency of the 1904 Oslo earthquake. It can be seen that the old Wiechert has better specifications with respect to seismic sources of the size of the 1904 Oslo earthquake than modern instruments.

CONCLUSIONS

Invaluable information on strong motion seismology is available in early seismic recordings. Unfortunately, these recordings have not yet been systematically compiled and are still scattered in various places around the world. Since a large seismic event is representative of a large tectonic region, a centralised compilation of records from large earthquakes is believed essential. Further work is also required on the characteristics of the early instruments.

ACKNOWLEDGEMENT

The Uppsala recordings were made available by Bjerking Ing, who also performed the digitising and spectral analysis of all the records. The seismic material was compiled by the International Seismological Centre. I am grateful to Roger Sidey for helpful discussions.

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Discussion on Papers 11 and 12

MR B.M. NEW (Transport and Road Research Laboratory, Crowthorne): I was most impressed by the correlations shown by Dr Medearis (Figs 1-5) between the actual structural motions measured and their analytical models. Were these analytical models produced as true predictions before the explosions or was there some feedback of data subsequent to the event?

DR MEDEARIS (Paper 11): The analytical models of the structure were developed prior to the event. Initial structure response predictions were necessarily based on predicted ground motions. The correlations shown were obtained using the actual recorded ground motions. They depict comparisons of the recorded and theoretical structural responses.

DR P.L. WILLMORE (Institute of Geological Sciences, Edinburgh): Dr Medearis, was your prediction of structural motion based on the actual earth motion of the large blast, or on a record of a previous blast?

DR MEDEARIS: It was based on a record of a previous blast, scaled up.

DR WILLMORE: Could you have achieved any comparable success without the assistance of the preceding blast at the same focus?

DR MEDEARIS: It would have been a more difficult comparison, but the two blasts were 100 miles apart.

PROFESSOR D.J. JOHNS (University of Technology, Loughborough): Could Dr Medearis comment on his structural models and whether he needed to refine these following preliminary tests. I have in mind in particular the levels of structural damping assumed in the multi-mode systems such as the tower. Considering the excellent correlation between 'theory' and experiment, would he consider his choice of damping(s) lucky - assuming he made no preliminary tests on this parameter?

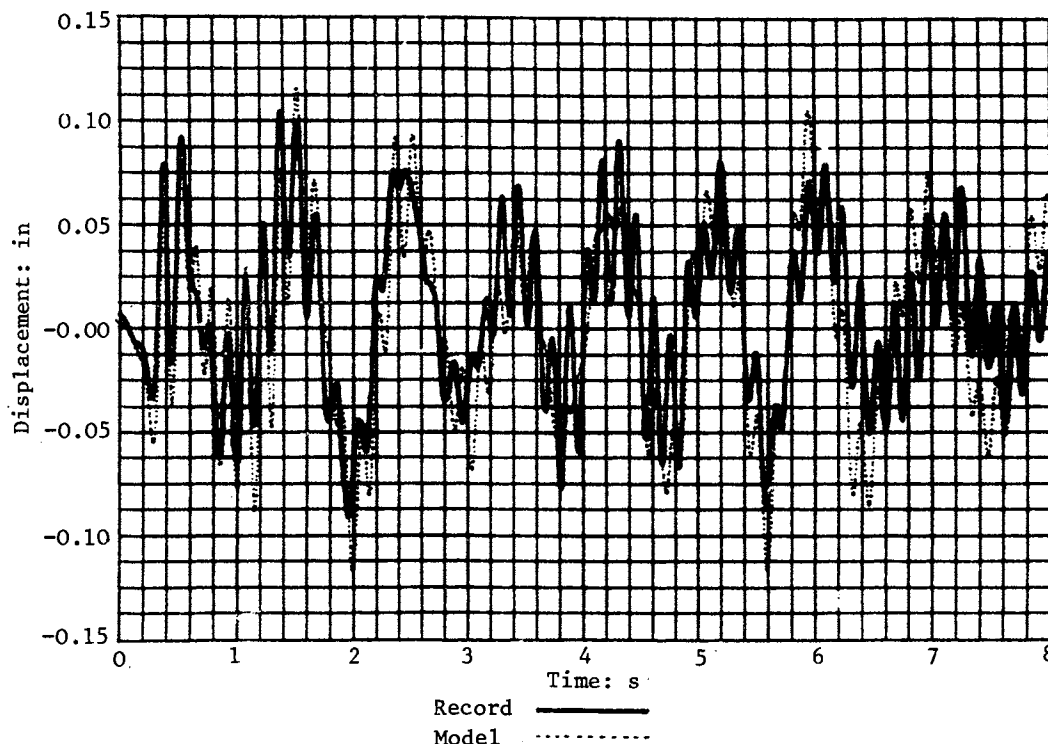


Fig.1. Chadbourne depropanizer radial response at top

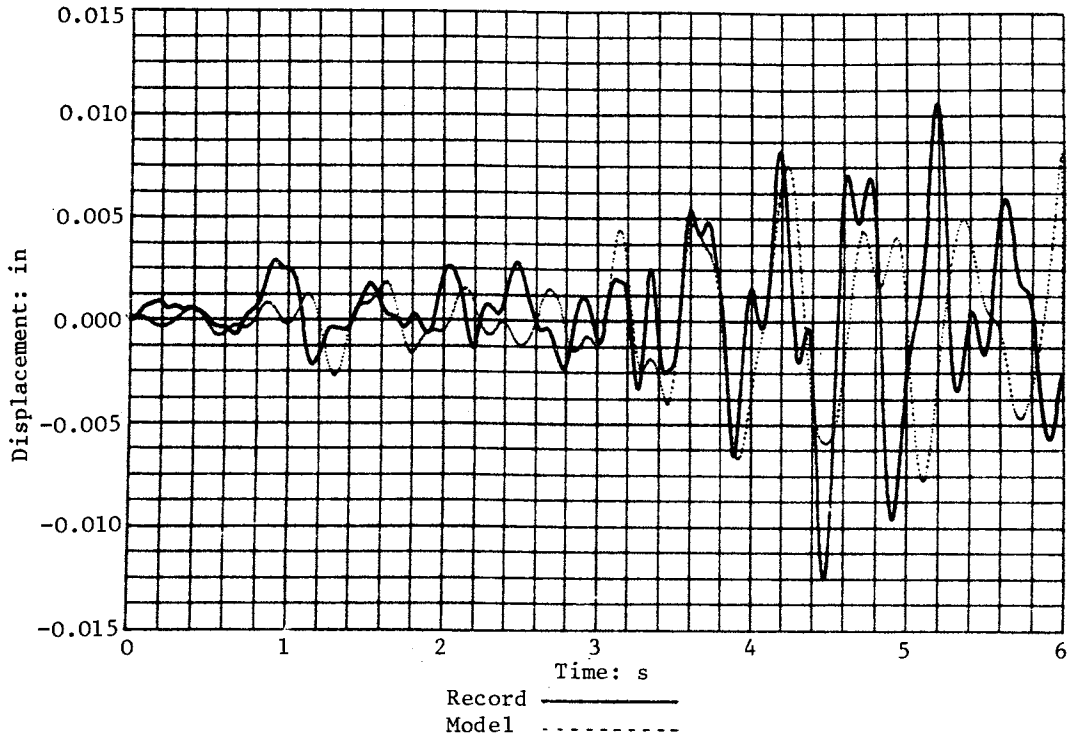


Fig.2. Harvey Gap dam transverse response at crest

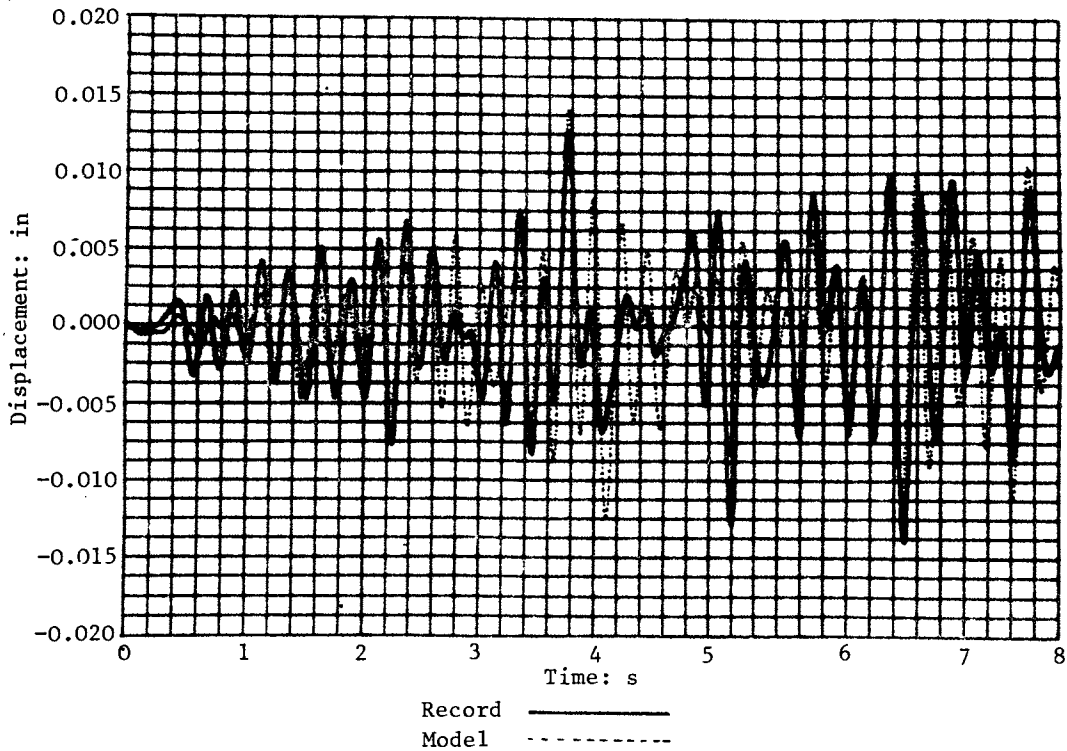


Fig.3. Rangely College gym transverse response at west end

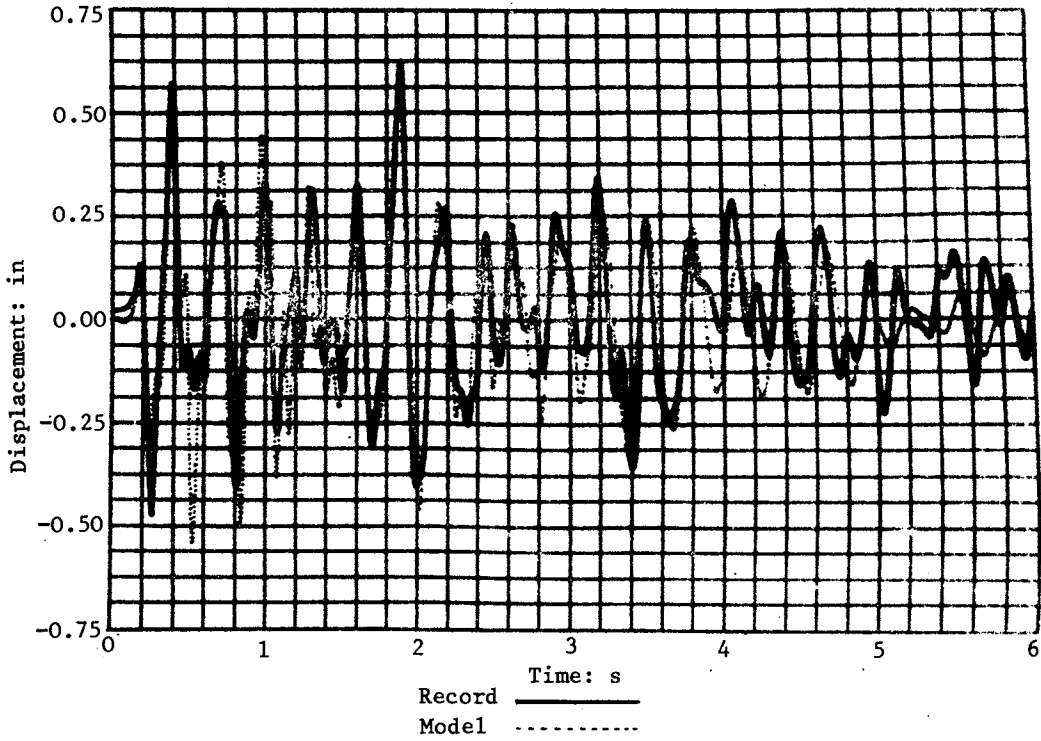


Fig.4. White River tower transverse response at top

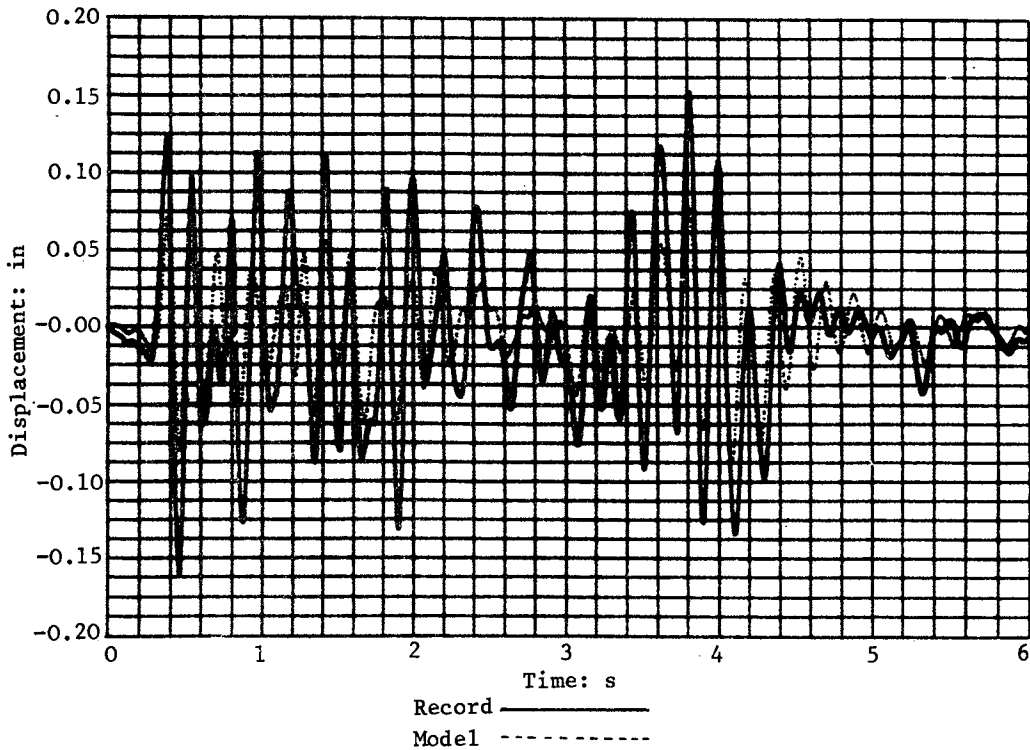


Fig.5. Rock School residence radial response at ridge

DR MEDEARIS: No refinement of the analytical models was found to be necessary. Structural damping values were varied somewhat for the analyses, being based on our various research and analytical efforts since 1960. (Two of the former projects were specifically concerned with determining the damping properties of structures.) The response contributions of the first and second modes were dominant for all of the structures investigated. The results shown (Figs 1-5) were those corresponding to the damping values which gave the best agreement. No experimental determinations were made since good agreement was achieved using assumed values based on our experience. Those values varied from about 1% to 8% of critical, depending on the specific structure.

MR R. BALL (Lanchester Polytechnic, Rugby): Would Dr Medearis clarify whether acceleration or velocity transducers were used, as §§3-5 of his paper mention a velocity seismograph and double integration of the output signals.

DR MEDEARIS: The ground and structure motions were indeed recorded using velocity transducers. However, those recordings were converted to accelerations by another organization prior to being given to us. A double integration was thus necessary to obtain displacement values.

MR C.P. LEWIS (Lanchester Polytechnic, Rugby): Would Dr Medearis comment on the use of accelerometers followed by a double integration process using a low frequency cut-off rather than the suppression of drift in the numerical processing of the velocity signals.

DR MEDEARIS: As stated, velocity transducers were actually utilized but the results were provided in the form of acceleration values. Inasmuch as those values were sufficiently inaccurate that derived displacements were found to be grossly incorrect, we would have preferred, in hindsight, to have received the original velocity values. Those also would have required correction, however. Further, we would still have needed to derive acceleration time-histories for input to our structural dynamics computer programs.

DR P. SRINIVASULU (Structural Engineering Research Centre, Adayar, Madras, India): What was the need for numerically differentiating the particle velocity records and again doing double integration to get displacement history? Does this operation not induce numerical inaccuracies? This, however, does not seem to have occurred as observed from the illustrations shown during the presentation. There was pretty good agreement between the theoretically predicted and measured (or deduced) displacements.

The prototype structures studied range from highly flexible to very rigid structures. It is generally believed that for realistic dynamic response of especially rigid structures, the mathematical model should incorporate the influence of soil-structure interaction. Has Dr Medearis considered the influence of soil in his mathematical model for prediction of structural response? I am interested in knowing at

least in brief the details of the mathematical model he has used for a very flexible and a very rigid structure.

DR MEDEARIS: As stated, the records were provided in acceleration form, and thus a double integration was necessary. The inaccuracies in the information provided, as well as those occurring as a result of integrations, were successfully eliminated using the correction procedures described in the paper.

Soil-structure interaction was considered for the structures analysed, which are all rather flexible. It was not found to be significant, with the exception that one of the structures was an earth dam. Such interaction is, in our experience, more dominant with quite rigid structures such as the foundations for power plant rotating machinery.

MR M.J. BALL (Nobels Explosives Company Ltd, Newcastle-upon-Tyne): It was interesting to hear of Dr Medearis's experience in monitoring ground vibration produced by a peaceful nuclear explosive (PNE) and of the eventual use of amplitude as a criterion for assessing damage risk. In the UK we also adopt a two-fronted approach to assessing risk, based on peak particle velocity, and at low frequencies (below 10 Hz) on peak amplitude of displacement. This latter criterion has been successfully used over the past 30 years and certainly appears to confirm Dr Medearis's philosophy.

Could Dr Medearis comment on why the authors take amplitude as the criterion, and could he comment on the so-called radius of 'damage zone' whose centre is the confined PNE? What levels of vibration might be expected at, say, 10 km radius from such a 90 kt device?

DR MEDEARIS: Amplitudes are depicted in Figs 1-5 primarily to show response time-history comparisons. However, in most cases, the material stresses were also computed in assessing whether or not damage was likely to occur. A research study we have recently completed, concerned with damage criteria for low-rise structures subjected to blasting vibrations, indicates that spectral velocity response is probably the best damage indicator for such structures (20 Hz or less).

A 50 km radius was utilized for the investigation described to ensure an accurate assessment of potential damage. The peak ground acceleration at 10 km was of the order of 0.33g.

MR I.P. HAIGH (Sir Alexander Gibb and Partners, Reading): Equation 5 of Paper 12 may be taken out of the context of the paper and usefully applied to the risk of damage occurring to rigid structures, particularly buried structures, as the result of ground motion. The assumption is that the response of these structures will be the same as that of the ground motion.

The equation shows that the elastic strain within the structure will be equal to the maximum particle velocity divided by the celerity of the shock wave. Within the limits of accuracy needed, the modified formula is equally applicable to longitudinal and shear waves; it is readily derived from kinetic and strain energy considerations.

DR WILLMORE: I think we all agree that the actual cause of damage to the structure is the relative displacement between parts of the structure. This is not the same as the displacement of the ground at foundation level.

Paper 1 is concerned with the best single-parameter description of earth motion. Acceleration input gets more destructive as duration increases. A given earth displacement gets more destructive as rise time diminishes. For this reason, velocity amplitude, which produces symmetrical excitation of a simple pendulum, with gradients of a log-log plot being unity on either side of resonance, is likely to be less severely inadequate than acceleration or displacement, each giving gradients of two on one side of resonance, especially if the frequency range over which the velocity amplitude is studied encloses the principal resonance of the structure.

MR R.G.T. LANE (Sir Alexander Gibb and Partners, Reading): Dr Medearis has demonstrated the viability of the calculation of response of structures at various levels compared to the assumed or measured ground motion. There remains, however, the uncertainty (in fact, impossibility) of specifying a precise ground motion for design. It would be interesting to know whether these studies have led to any improvement in assessing a design ground motion - perhaps by working backwards from estimated response; and whether the work confirms the value of methods of design using response spectra, such as described by Newmark and Hall.¹

DR MEDEARIS: The primary purpose of the study was to verify that structural response can be accurately predicted using theoretical dynamic analysis. Ground motion predictions were based on previous nuclear detonations and proved to be relatively accurate. In my opinion, a statistical representation using velocity response spectra is the best approach. However, it seems questionable that enough earthquake records have been utilized in generating existing representations. I believe that more work needs to be done in this area, and that velocity, rather than acceleration, will prove to be a better criterion statistically. The latter is certainly true of our recent analyses of some 200 blasting ground motion records.

MR K. FULLARD (Central Electricity Generating Board, Berkeley Nuclear Laboratories): The question of predicting ground motion for use in aseismic design has been raised. My comment relates to the situation in the UK, which is different from that in the USA. There, a body of accelerogram data exists and has been used to produce the smoothed design response spectra of the Nuclear Regulatory Guides. Our situation is that no such equivalent body of data exists for the UK. A small number of the US acceleration time-history records may be deemed relevant to the UK; i.e., measured at distances from the source comparable with our depths and of magnitude events equivalent to those at the upper end of our events. These are so few that it would be difficult to justify a set of smoothed design response spectra for UK use. My expecta-

tion is that the actual response spectra of relevant records will be used by designers to establish displacement or stress levels in initial calculations. These would be relatively cheap to carry out since a full transient analysis is not involved. Only if high displacements or stresses were found would transient analyses be carried out, and then only if economically justified, using those relevant US acceleration time-histories.

DR P.W. BURTON (Institute of Geological Sciences, Edinburgh): Further to Mr Fullard's remarks, I would add that in all cases a suite of earthquake time series data should be used for building response analysis. Analysis based on one time series alone will not allow for the statistical variability observed in earthquake records, whereas a suite of 'characteristic' records will allow for both statistical and physical variability in ground motion generated by earthquakes.

MR D. STRINGER (Watermeyer Legge Piesold and Uhlmann, Ashford, Kent): Dr Medearis, I would like to know how the soil properties needed for the dynamic analysis of the earth dam on which you conducted your tests were obtained.

For the design of a new earth dam, would you consider it acceptable to derive the soil properties used in dynamic analysis from measurements of S and P wave velocities carried out at the site investigation stage on trial embankments?

DR MEDEARIS: The soil properties utilized for the dynamic analyses of the earth dam were obtained by taking micro-vibration measurements on that structure, then equivalencing the experimental results with those obtained analytically. That is, the soil properties utilized were those which give agreement between the experimentally and analytically obtained frequencies.

The answer to your second question is yes - with proper consideration of non-linear soil properties as might be required for the specific situation; i.e., possible stress levels, earthquake magnitudes etc.

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13. Investigation of earth tremors at Stoke-on-Trent

G.K.WESTBROOK, BSc PhD (Department of Geological Sciences, University of Durham)

The installation of a seismic network in Stoke-on-Trent, following the occurrence of earth tremors there in 1975, enabled accurate location of the focii of subsequent tremors. Analysis of the data from the network has established that the earth tremors were mining induced.

INTRODUCTION

1. Several areas in North Staffordshire have experienced occasional series of earth tremors, which are known locally as 'goths' or 'bumps', since the latter part of the last century. The Stafford Earthquake of 1916 was quite different in size and nature from most of these tremors (ref. 1). In late January and early February 1975 some small tremors were felt in the Trent Vale area of Stoke-on-Trent. A number of these were recorded in the area with a three component set of seismometers operated by the author on behalf of the National Coal Board.

2. In the evening of July 15 1975 a strong tremor (Modified Mercalli Intensity 6) shook the area of Trent Vale and Hanford followed by another tremor which affected the Knutton-Silverdale area. More tremors occurred in the following weeks. Following the 15th of July tremor, the Seismology Unit of the Institute of Geological Sciences carried out a macroseismic survey and with the Geology Department of the University of Keele, began to install a network of seismometers to monitor and locate the earth tremors. The investigation was supported by a working party set up to find the cause of the tremors in response to the public concern the tremors aroused.

3. The installation and operation of the network, the analysis of the data provided by it, and the initial interpretation of the results obtained from the area of Trent Vale and Hanford are the subjects of this paper.

THE SEISMOMETER NETWORK

4. The distribution of seismometer stations around Stoke-on-Trent is shown in Fig. 1. The main element of the seismometer network was the Rascal Geostore System. A 14 track tape recorder was situated at Keele University, with four seismometers there (one three component set and one vertical outstation) connected directly to the recorder by cables after amplification and frequency modulation. Four outstations distributed around Stoke consisted of one vertical Willmore MkII seismometer (with a natural frequency of about 0.5 Hz) connected to an amplifier/modulator, from which the

amplified and modulated signal was transmitted via a U.H.F. radio link to the main recorder at Keele. In addition to the four radio linked outstations, there were two stations with their own recorders and three-component sets of seismometers (ref. 2). All the recorders recorded the M.S.F. 60 KHz radio time signal to give an absolute time reference for the seismic signals.

5. In siting the seismometers several considerations needed to be taken into account. These were:-

- a) The overall geometry of the network must be such that the earthquake hypocentres are well defined both in epicentral position and depth. (ie there must be a wide variation in range and azimuth of the stations from the epicentres).
- b) The ambient noise from various non-seismic sources such as traffic, industrial machinery and wind, must be at minimum. This was accomplished by avoiding the vicinity of obvious noise sources and by siting the seismometers on, or as close as possible to bedrock, to reduce the ratio of surface transmitted noise to seismic signals travelling through the rock.
- c) The recording apparatus must be secure from theft and damage.

These requirements sometimes conflict. Of the seven different installations three were sited in purpose-built pits with concrete floors, three were in concrete floored outbuildings and one was in the basement of a large house. A further requirement for the radio linked sites was that they should be in line of sight of the base station where the recorder was.

6. The advantages of the radio linked outstations were that they were all recorded on the same tape, saving tapes and making replay of the records and time correlation between stations simple. Also with long lasting batteries the stations did not need frequent visits to change tapes. Disadvantages were that if the recorder broke down, all stations

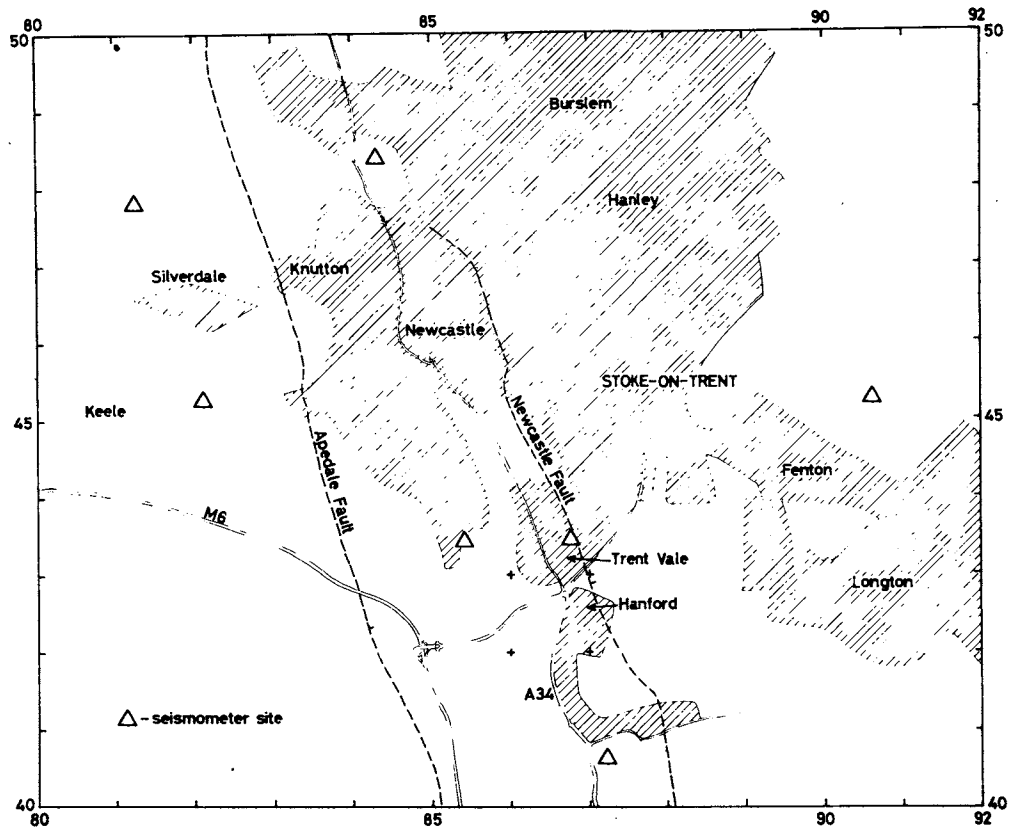


Fig.1. Map of the general area of Stoke-on-Trent and Newcastle-under-Lyme, showing the positions of seismometer stations (open triangles). Diagonal ornament shows built-up areas. National Grid at 1 km intervals is also shown

were lost, and that three weeks delay was encountered in obtaining permission from the Post Office for the radio frequencies used, which prevented rapid installation of the whole network to record the first series of tremors in late July and August. The self contained sets can be installed quickly and, being independent, the failure of one recorder does not disable the whole network. They did, however, require more attention than the radio linked sets once the network was installed and involved much more work replaying the magnetic tapes - one for each station instead of one for all.

DATA ANALYSIS

7. Tapes from the main recorder were initially played back on to a paper record at about 40 times real time to identify any local seismic events. The earth tremors generally had clearly identifiable characteristics and were easily distinguished from other nearby seismic sources such as quarry blasts. After this initial screening, recordings from local earth tremors were replayed at slower tape speed and faster paper speed to give more detailed records of the events so that the arrival times of seismic waves could be identified to an accuracy of about 1/50th of a second and the amplitudes of arrivals measured. The dominant frequency of p-waves from the tremors was about 12 Hz.

8. Once the arrivals had been measured the hypocentres of the tremors were located using a computer program which employs a non-linear optimisation routine (ref. 3) to find the position of the hypocentre giving the minimum variance between the observed and theoretical travel times. Considerable care was taken to determine the best seismic velocity parameters for the rocks through which the waves travelled. Initial estimates were obtained from sonic logs in exploratory boreholes drilled for the N.C.B. in the area; these were used as the starting values for computation of joint-hypocentral determination in which the velocity structure that gave the best fit for a group of hypocentres was found. These estimates were confirmed later by setting off an artificial charge down boreholes close to the region in which the tremors occurred. The best structure was one with a linear increase in velocity with depth of 1.2 s^{-1} and a velocity of 3.2 km s^{-1} at sea level. Head waves refracted at a major geological boundary at depth did not occur as first arrivals at any stations because of the short ranges involved in the network. The errors of most of the hypocentres were better than $\pm 400 \text{ m}$ at the 95% confidence level.

RELATIONSHIPS BETWEEN EARTH TREMORS, GEOLOGY AND MINING

9. The locations of tremors (epicentres) located during 1976 are shown in Fig. 2. Running in a north-northwesterly direction east of most of the epicentres is the Newcastle Fault, which dips to the east and downthrows the Newcastle Formation on its eastern side against the Etruria Marl on its western side.

The tremors which occur between 1 km depth and the surface are all in the Upper Coal Measures. The areas have been quite extensively mined; the Bowling Alley and Moss seams, at average depths of 930 m and 690 m respectively, having been extracted in the late 1940's and mid-1960's. During 1976 the Ten Feet seam was being extracted along a panel (205's) moving southward, parallel to the Newcastle fault and west of it, at an average depth of 900 m. The roof was allowed to cave completely following extraction. Three other panels had already been taken between it and the fault, and the previous panel 204's was being mined during the period of tremors in 1975. The outlines of these panels are shown in Fig. 2.

10. After early September in 1975 only two more tremors were felt in Trent Vale, although over thirty were detected by the network, until early April 1976 when a new series of felt-tremors began. These felt-tremors did not cease finally until November 1976, and tremors of smaller size were detected subsequently. Some of the results of the investigation relating to the main period of felt-tremors in 1976 from 20th March until 31st August are described below.

11. Figure 3 shows the occurrence and size of tremors through this period. The estimator for size is the maximum ground velocity produced by p-waves at the seismic station furthest from the epicentral area. Differences in range are small compared with the distance travelled, and therefore the amplitudes can be directly compared. The size and frequency of tremors reached a maximum in June, gradually decreasing through July and August with a 12 day break in late June and early July (days 178-190), which corresponds to the holiday period in the mines. If one considers how the tremors are distributed through the week (Fig. 4) it is clear that most tremors occur on week days, Thursdays being particularly active. This distribution corresponds closely with activity in mining the 205's panel during the week.

12. Figures 5, 6 and 7 show respectively in plan, west-east cross-section, and south-north cross-section, the spatial distribution of the hypocentres (focii) of the tremors in relation to mine workings and the Newcastle Fault. The radii of the circles around the locations are proportional to the amplitudes of the tremors as shown in Fig. 3. The area between the two dashed lines on the 205's panel in Fig. 5 and between the two arrows in Fig. 7 show the region extracted during the period 20 March - 31 August. Nearly all the tremors plot above the panel, and given the errors of location it is possible that those which plot below also occurred above the panel. The hypocentres occur in a planar zone running perpendicularly to the direction of advance of the panel and at right angles to the surface of the panel. Control on hypocentral positions is better in the north-south component than the east-west one because of the shape of the network, and consequently some of the east-west scatter in

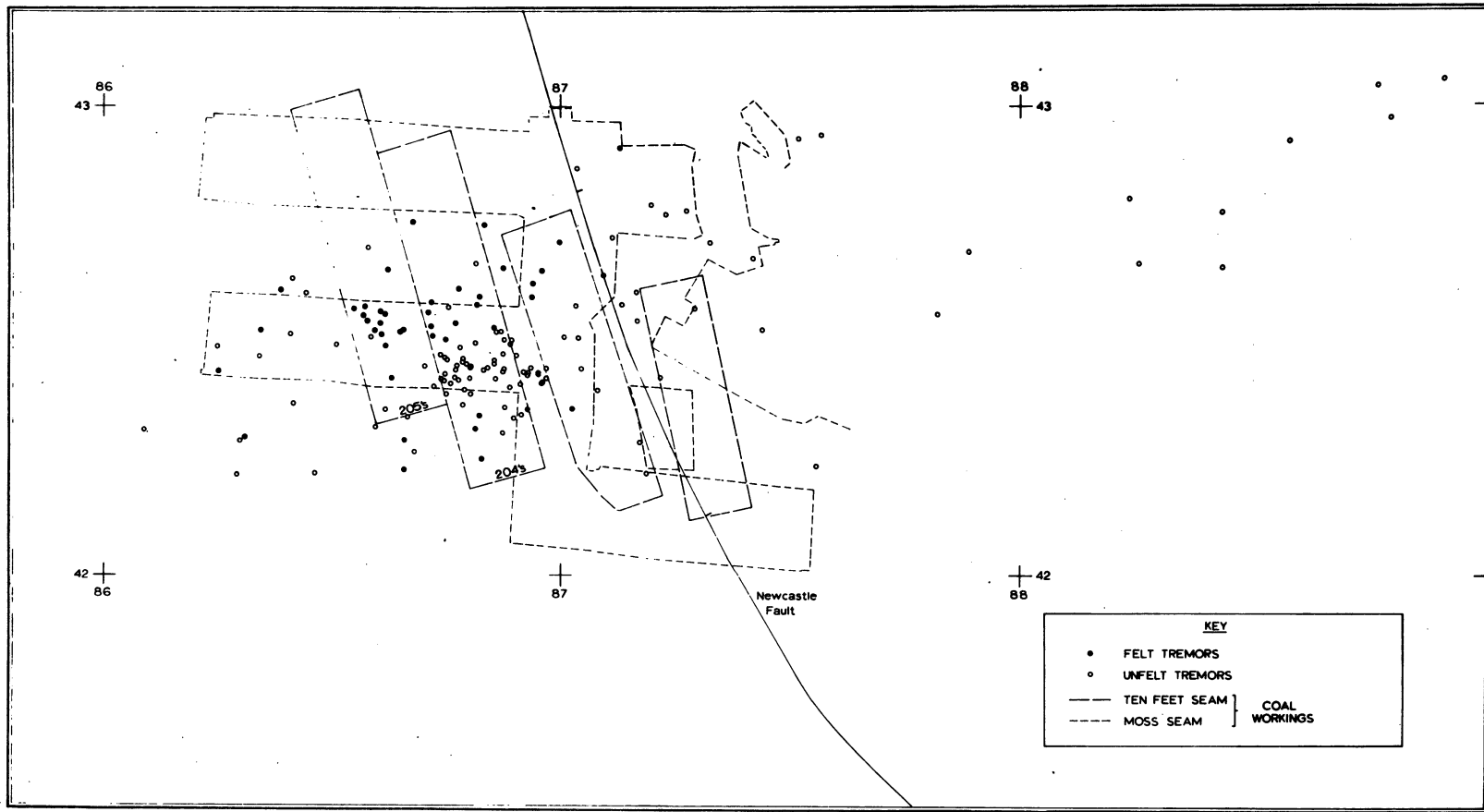


Fig.2. Plan showing epicentres of earth tremors in the area of Trent Vale and Hanford for the period 20 March 1976 to 20 November 1976. Also shown are the outlines of coal workings in the Moss and Ten Feet seams

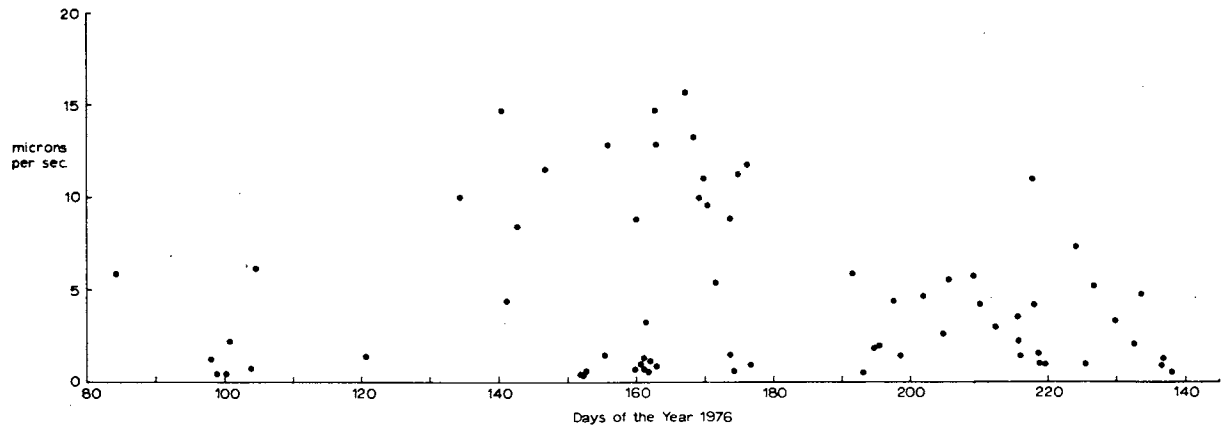


Fig.3. Graph showing maximum velocity of ground motion from p-waves produced by earth tremors at a station 6 km away from them plotted against their day of occurrence

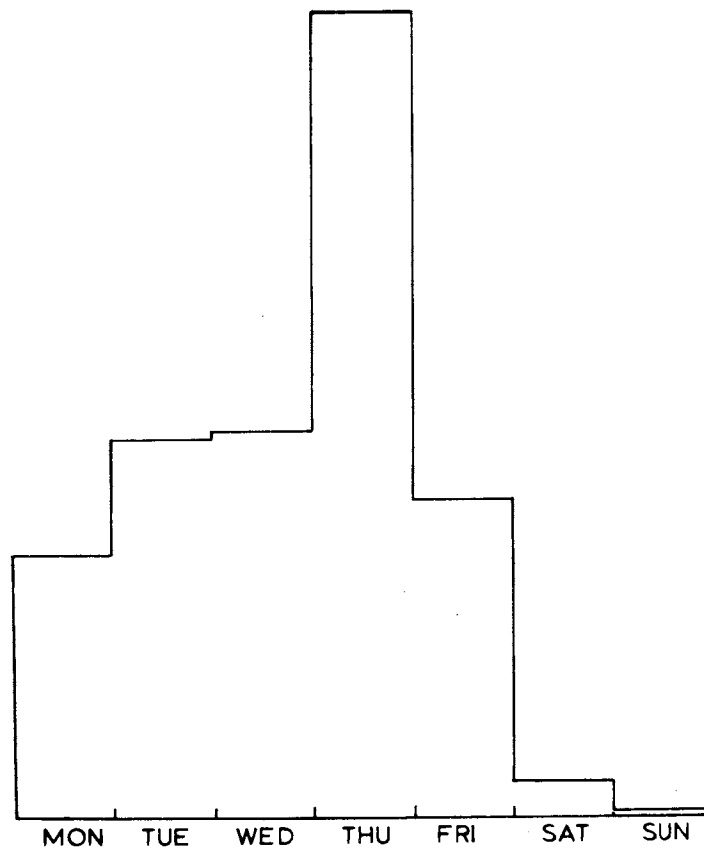


Fig.4. Histogram showing relative amounts of seismic energy released per day of the week

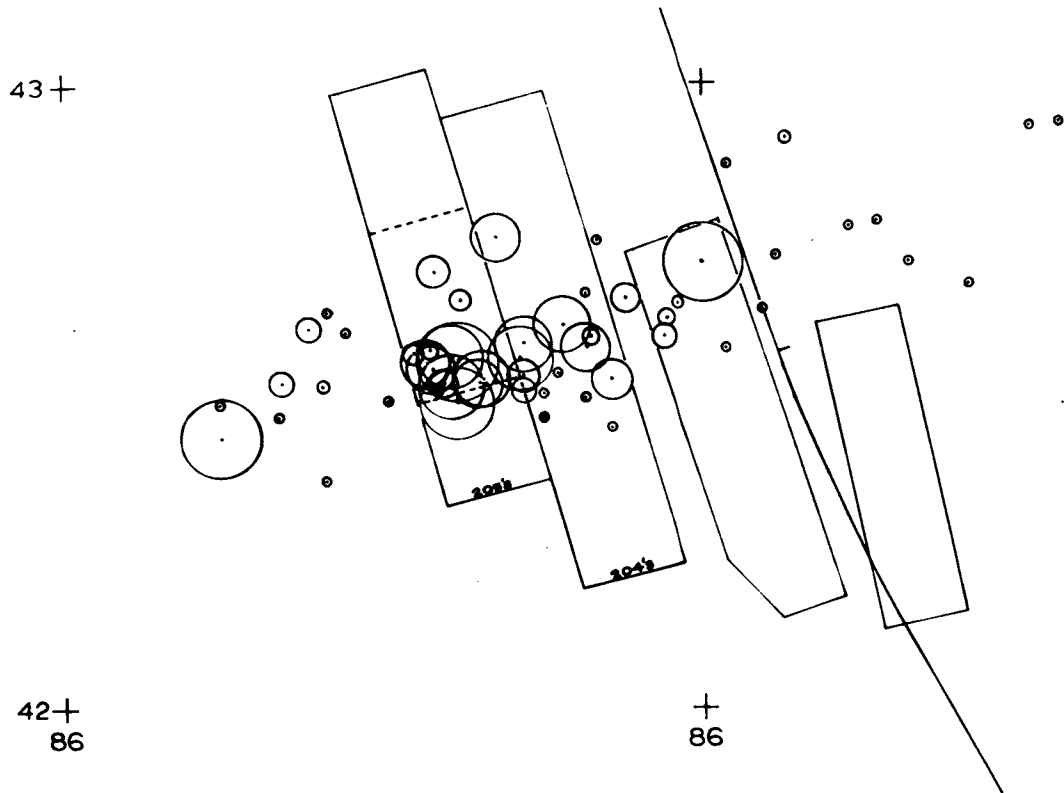


Fig.5. Plan showing epicentres of tremors occurring in the Trent Vale area during the period 20 March to 31 August 1976. The grid intersections are 1 km apart and are also shown in Fig.1. Circles around epicentres are proportional to amplitude. Also shown are the outlines of the panels in the Ten Feet coal seam. The area between the dashed lines in 205's was mined during the period in which the tremors occurred

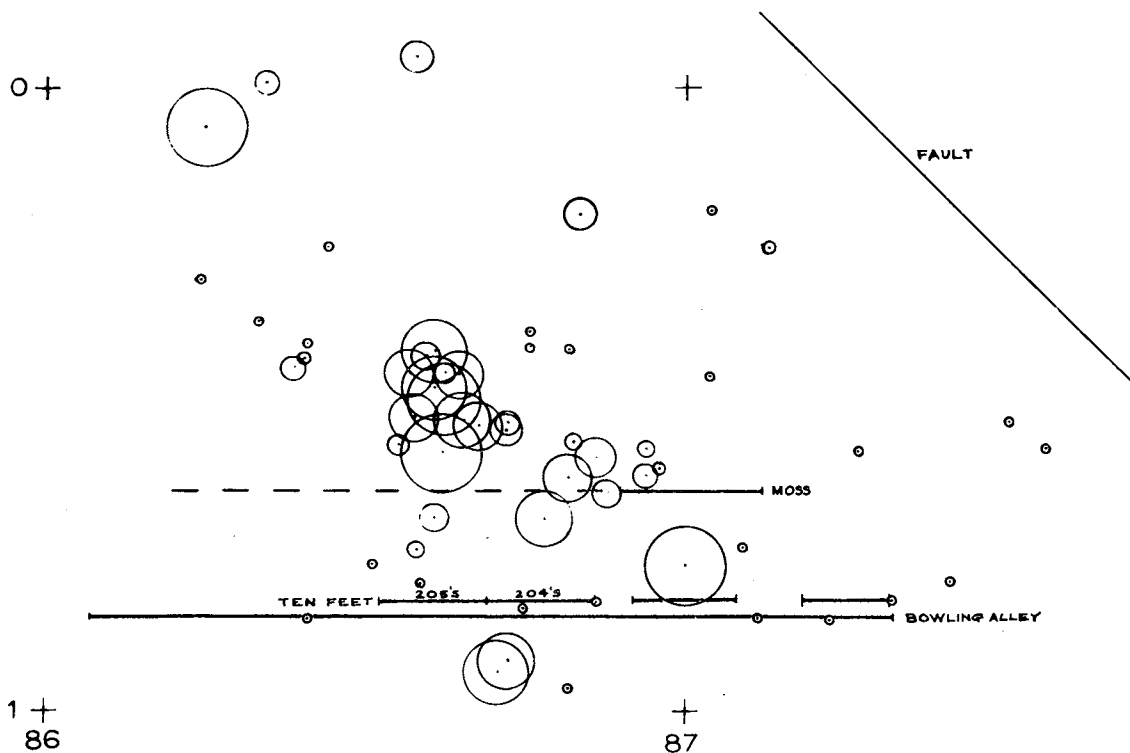


Fig.6. West-East cross-section through area shown in Fig.5, showing relationship between earth-tremor hypocentres and coal workings

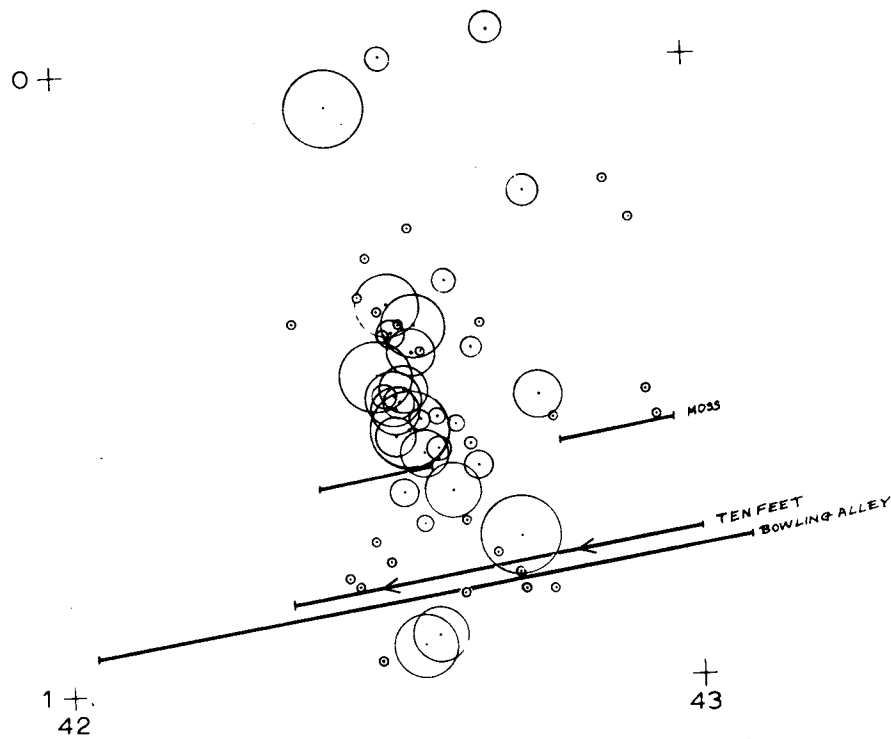


Fig.7. South-North cross-section through area shown in Fig.5, showing relationship between earth-tremor hypocentres and coal workings. The region between the two arrows on the Ten Feet seam was extracted during the period in which the tremors occurred

positions is caused by this. During the period, the locations of the hypocentres showed no variation in position related to change of face position, but during September, October and November the hypocentres generally migrated southward with the coal face. The hypocentres are well away from the Newcastle Fault and it appears to have played no active part in producing the tremors, which is interesting because it is an obvious line of weakness and movement on the fault might have been expected from differential subsidence on either side of it. There is also no other fault (even a very minor one) in the zone of hypocentres.

13. It is clear from the spatial and temporal correlations with mining activity in the Ten Feet seam that the tremors are mining induced, but the mechanism by which the tremors are produced has still to be determined. A preliminary analysis of the directions of the first motions of the ground caused by tremors has shown that the majority have motions caused by movement on some form of slip plane. There is more than one plane, but there are not sufficient stations to accurately identify the orientations of these planes. Some of the deepest tremors, however, gave first motions which were dilatational at all the stations, implying some form of implosional mechanism.

14. The older workings above and below the Ten Foot Seam might possibly be important in influencing the stress field around the panel, but collapse of old workings is unlikely. The Moss Seam was allowed to cave when it was mined. There are no workings of the room and pillar type in the vicinity.

15. The likelihood of the event of 15 July 1975 being atypical, and maybe having a different cause, has been significantly reduced by the analysis of the macroseismic survey of this event carried out by Dr. C.W.A. Browitt. This was compared with a similar survey of an event on 13 May 1976 for which instrumental data were available. Both macroseismic analyses indicate depths less than 1 km.

16. While the event of 15 July 1975 caused minor damage to buildings, the amount of damage caused by later tremors is less clear. The properties in which damage has claimed to have been caused have also been directly affected by mining subsidence which is undoubtedly the main cause of damage. Estimates of maximum ground velocity derived from the measured velocities at the seismometer stations do not exceed 10 mm s^{-1} .

17. Work is in progress to provide more data on

the detail of the tremors. A further five seismometers which have been sited in an area of one square kilometre directly over the 206's panel (i.e. west of 205's), will reduce the errors in location of the hypocentres of the tremors to about 50 m. This may enable individual failure surfaces to be identified. Also, an analysis of the orientations of joint planes is being undertaken by the N.C.B.

CONCLUSIONS

18. The installation of a seismic network at Stoke-on-Trent has been effective in accurately locating the hypocentres of earth tremors, most of which are not felt by people, thereby providing valuable information on the cause of the tremors. The analysis based on the data from the network has ruled out movement on natural faults, collapse of old mineworkings and underground explosions as possible causes. The correlation between the earth tremors and current mining activity has been clearly established, but the nature of the mechanism producing the tremors is still unclear.

ACKNOWLEDGEMENTS

19. This work was carried out while I was lecturer in geophysics in the Department of Geology, University of Keele, and I am grateful to Dr. B.K. Holdsworth, M. Wright, J. Lawrence and J. Singh for their help and assistance in setting up and running the network. Most of the equipment was provided by the Seismology Unit of the Institute of Geological Sciences and Dr. C.W.A. Browitt was principally responsible for setting up the network and arranging the macroseismic surveys, ably aided by Mr. B. McGonigle. Dr. R.E. Long of the University of Durham provided two seismic recording units for the independent stations. Mr. R. Hoare and Mr. A. Brockley of the N.C.B., Western Area have provided much information concerning mining operations, subsurface geology and ground subsidence. The investigation was initially supported financially by the National Coal Board and Stoke City Council, with more finance coming later from the Department of the Environment, Staffordshire County Council, and Newcastle-under-Lyme Borough Council.

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14. Investigation of vibrations caused by released forces in the iron mine of Grängesberg, Sweden

L. STENLING, BSc (Nitro Consult AB, Stockholm)

Earth tremors represent a problem in modern mining. Not only as a safety risk but also because of its psychological effect on human beings living close to mines. Continuous monitoring and recording supervision gives a valuable information on the seismic activity in the area and this is used to define more accurately the mountain slide risk zone. These data are also used as part of the information to the public. A measuring system is here described that provides the required information.

INTRODUCTION

1. In the middle of Sweden, in the District Bergslagen, one of the oldest mining areas is located. Mining is still carried out here and one of the largest mines is called Grängesberg. The mining here dates back as early as to the 16th century, at first as an open mine, later as an underground mine. The production today is executed at appr. 500m below surface. The capacity of the mine is 2.3 Mt per year of iron ore.

2. The ore body has the shape of a rectangular plate going down and tilting appr. 65 degrees. The size of a horizontal section of the ore body is 1500 m by 40 m. Fig. 1 shows a vertical cross section of the mine.

3. In earlier days the community was situated on the east side of the open mine, as shows in Fig. 1. At this stage, underground mining was not considered, neither were the problems of cracks and mountain slides in this kind of mine yet known, hence the unfortunate location of the old community.

4. As the production continued and the iron ore got excavated, the mining company became aware of the risk for mountain slides caused by the hanging eastern wall. Therefore the whole community was moved 500 m east to a safe location. This happened in 1930 well before the risks of mountain slides became apparent.

INVESTIGATION OF TREMORS

1. As shows in Fig. 1 the whole area consists of solid rock. Consequently as the iron ore is excavated, forces are built up in the rock as it tends to fall and fill out the open space. These forces are built up gradually and eventually reach a point where the tensile strength of the rock is exceeded. At this point the rock breaks and earth tremors are created. The level of those tremors vary widely from less than 0.01 mm/s to over 1 mm/s.

2. Normally the tremors are so small that they

can hardly be noticed in the community. In 1974, however, a heavy tremor accured which initiated an investigation project. An expert committée was formed and a two step measuring program started. The first step of the measuring program involved theoretical studies as well as practical measurements in order to establish the possibilities and means for monitoring, locating and possibly prediction of earth tremors.

3. The first step was completed late in 1975 and the conclusion was that monitoring as well as locating would be possible with adequate measuring equipment. The possibility to predict earth tremors was considered more difficult and further investigations were to be carried out during step two. After step one it was also possible to specify in detail the required measuring system. As a result, a new measuring system was composed and installed in September 1976 and the second step of the measuring program started. In the following, a description of the measuring system will be given.

THE MEASURING SYSTEM

1. Fig. 2 shows a map of the mining area. A dotted line indicates the fenced in area where cracks have appeared and the risk of mountain slides is apparent. Five measuring points are placed within the area and one outside it. The measuring points are identified as MP 1-6. The electrical signals are connected to the measuring instruments identified as MS.

2. The complete measuring system is showed in a simplified block form in Fig. 3.

3. Each measuring point consists of a vertical geophone securely bolted to a concrete fundament which is fixed to solid rock. The geophone is two folded protected from rain and snow. Firstly by a small metal box and secondly by a larger locked wooden box. The signals from the geophones are fed to the measuring instruments through screened cables. The maximum distance is appr. 2 000 m.

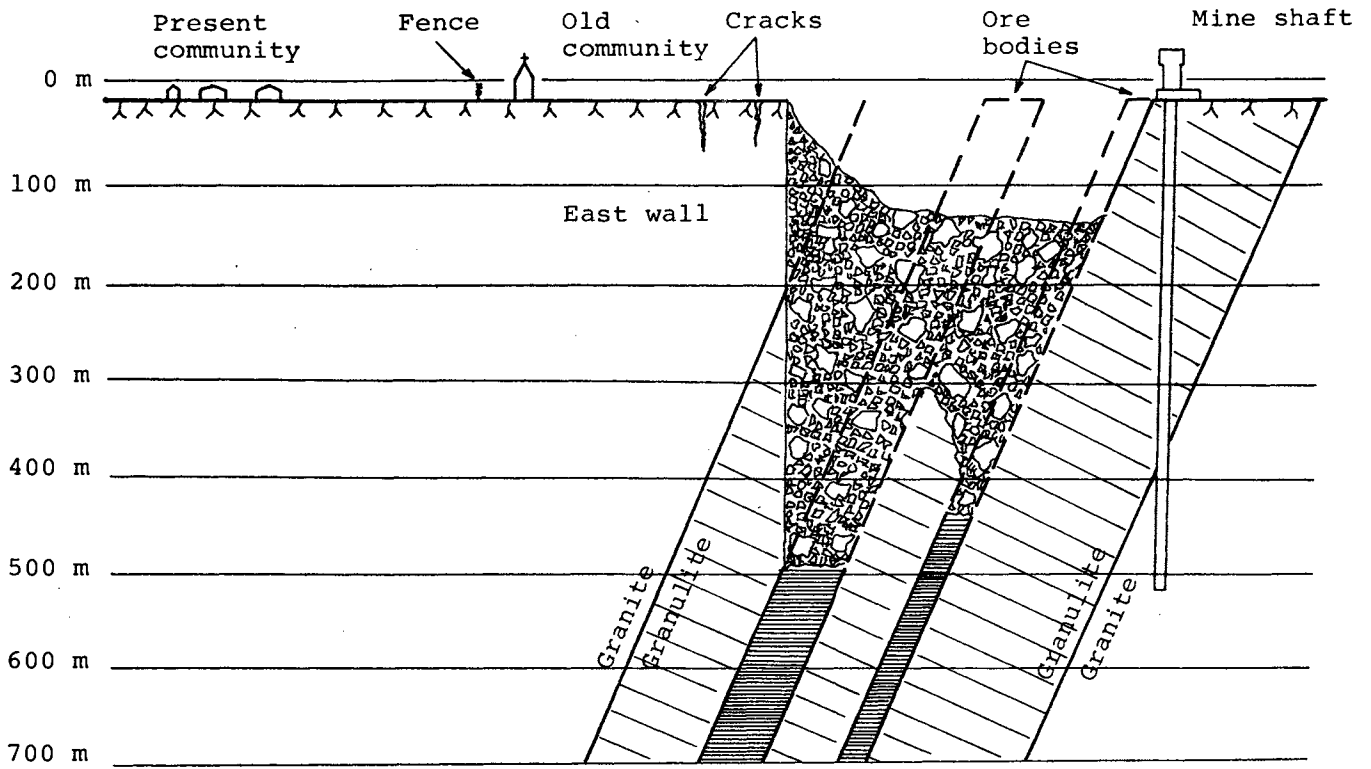


Fig.1. Vertical cross section of the mine

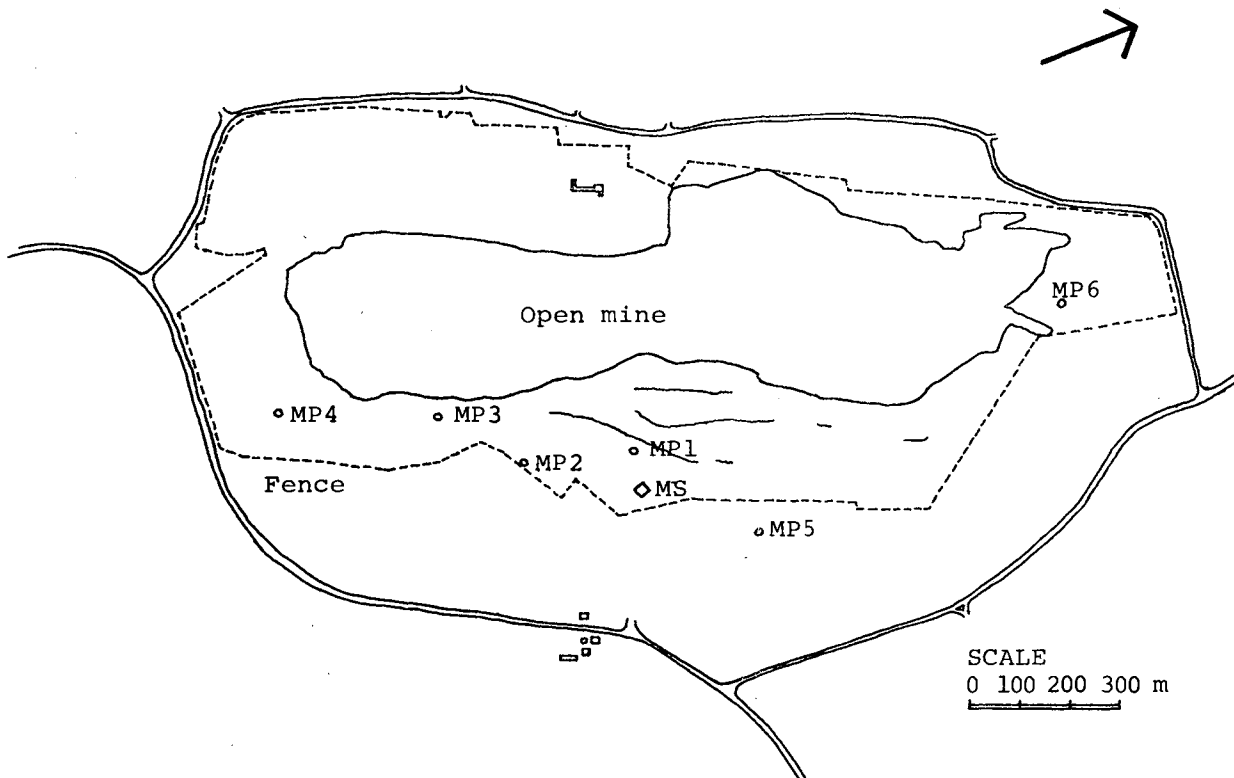


Fig.2. The mining area of Grängesberg

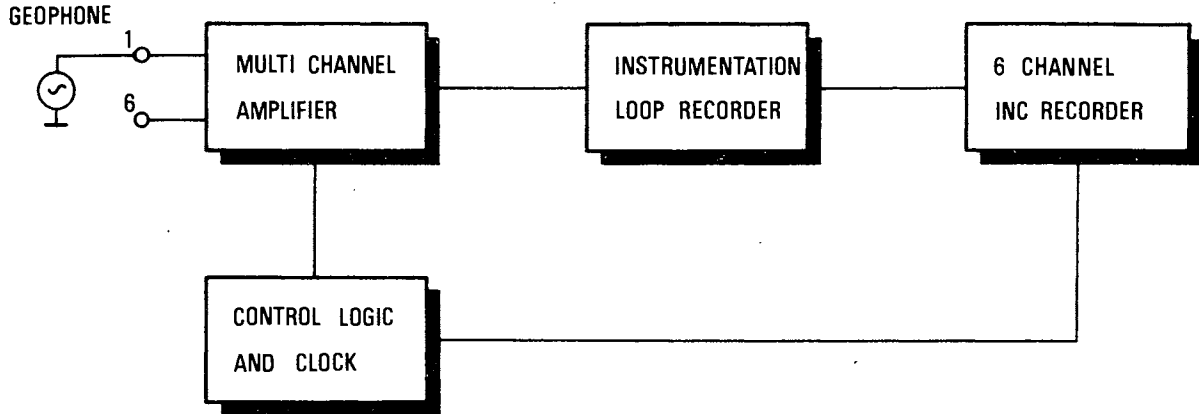
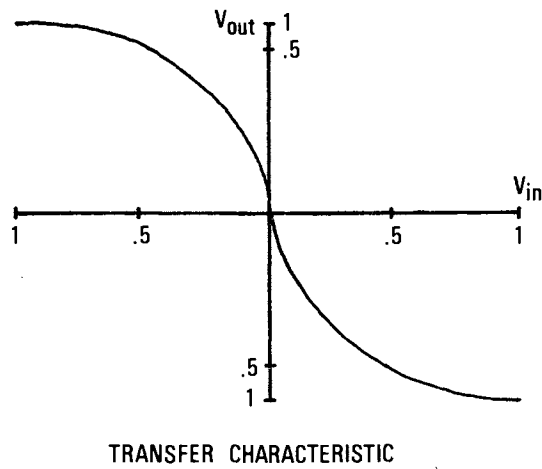


Fig.3. Block diagram of the measuring system



TRANSFER CHARACTERISTIC

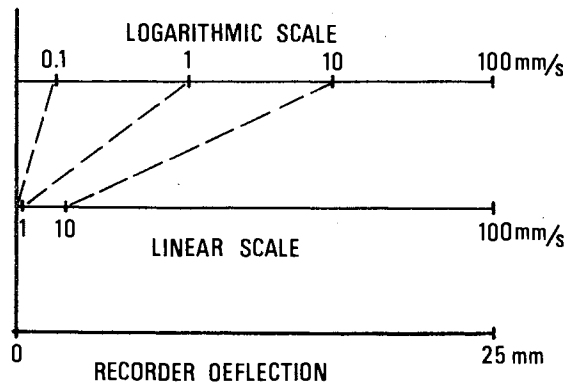


Fig.4. Comparison between linear and logarithmic recording

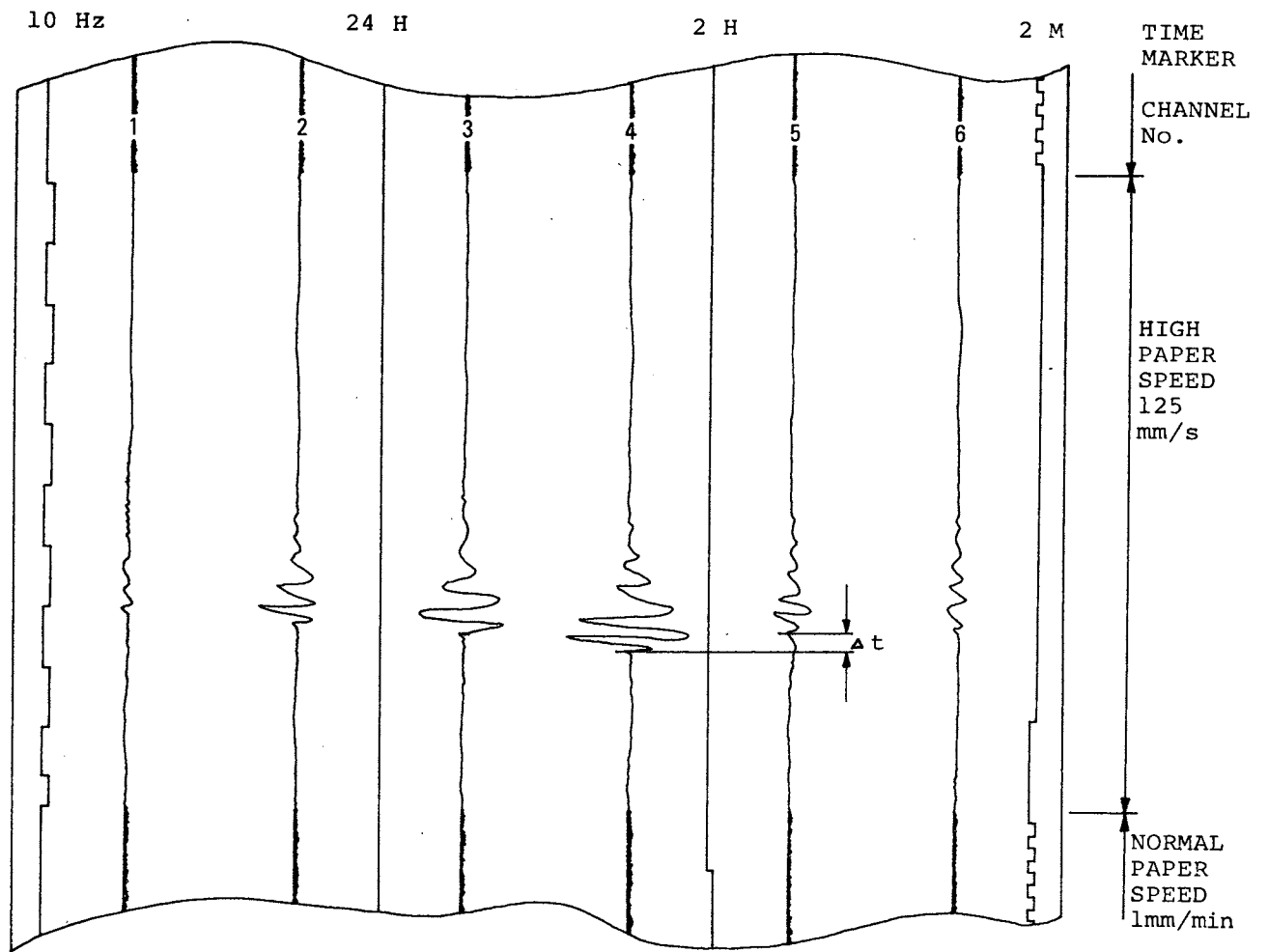


Fig.5. Typical six-channel recording

4. The signals coming in from the six geophones are connected to a multichannel amplifier for conditioning. The amplifier consists of a basic unit and a plug-in amplifier unit for each channel. The system is today equipped for six channels but can be extended to fourteen channels. The plug-in amplifier has a floating differential input giving the system high rejection to unwanted common-mode disturbances. The relatively high input impedance makes the system insensitive to variations in the resistance of the cable due to variations of length.

5. An interesting feature of the amplifier is the logarithmic amplification characteristic. This enables the system to handle and record, in an analogue form, signals over a wide dynamic range. It means that recorded signals can be evaluated accurately from 100 m/s to 1 mm/s. The resolution is better than 0.1 mm/s with full scale deflection of 100 mm/s. This is showed in fig. 4 where a linear scale also is included for comparison.

6. The amplifier is also equipped with a limit detector which enables the operator to set a trigger level, in this case between 0 and 2 mm/s. When the input signal exceeds this limit a relay is actuated and a contact closure is available at the rear panel for external control.

7. The output from the multichannel amplifier is connected to an instrumentation loop recorder, the purpose of which is to delay the signal by appr. 3 seconds. After the delay period the signal is played back and fed to a six channel ink recorder. This process goes on continuously.

8. The six channel ink recorder is modified so that two paper speeds can be chosen by remote control. Normally, when no seismic activities are present, the paper speed is as low as 1 mm/minute. When the seismic vibration exceeds the level set by the operator on the limit detector described above, the paper speed is immediately increased to the very high speed of 125 mm/s. The limit detectors are connected to the real time signals while the six signals connected to the ink recorder are delayed by 3 seconds. This delay allows for the ink recorder to increase the speed as well as to reach stable conditions and when the signals arrive the speed is constant. Fig. 5 shows in principle a typical recording.

9. To identify the exact time of the tremor, a time generator is incorporated in the system. The time generator consists of a crystal controlled digital clock giving hours, minutes and seconds, decoding and control logic. Four outputs are provided for the control of the four marker-pens on the six channel ink recorder. The four outputs are:

- a) 24 hours (20 hours on, 4 hours off)
- b) 2 hours (1 hour on, 1 hour off)
- c) 2 min (1 min on, 1 min off)
- d) 10 Hz (100ms) signal for control of linearity at high paper speed

In practice it is possible with this relatively simple coding system to identify the time of the tremor to within less than 30 seconds.

10. Sometimes the tremors appear over a relatively long period of time. There are also multiple tremors with a few seconds delay between each maximum. To make sure that no such information is lost the high paper speed of the six channel ink recorder will continue until all signals have gone below the trigger level. Further more a delay circuit is incorporated which enables the operator to add an extra 0-10 seconds, continuously variable, to the high speed recording time.

11. The measuring system is generally left unattended. Recordings are collected once a week paper is replaced when needed and a visual check is made.

12. Since it is required that the system shall operate reliably and continuously, a preventive maintenance program has been made up. This program includes a monthly minor inspection and a test program is carried out by the operating personnel. Every six months a complete test and calibration of the system is made by qualified staff from the service department at Nitro Consult in Stockholm.

13. An emergency plan has also been formed and if there is a break down of the system, that can not be eliminated by the operating personnel, experienced service personnel will be working at the site within 48 hours after a call.

14. The recordings are manually evaluated and the values are fed to a computer for calculation. The computer calculates the location of where the tremor has started by comparing the difference in time between the arrival of the wave at each measuring point and its travelling speed.

CONCLUSION

1. After six months operations this system has been evaluated, and the following observations have been made and considered relevant.

2. When high reliability and a minimum of down-time is required, the following points must be considered especially:

- a) The outdoor installation must be very thoroughly carried out. The transducers must be protected and the cables must be of high quality and well supported. The extra installation cost is soon payed off.
- b) The amplifier system must be designed to accept the sometimes large electrical disturbances. Our experience from the first step of the program proves this.
- c) The instrumentation loop recorder has not proved itself to be sufficiently reliable. An all solid state delay unit has been proposed and will be used in future systems.

3. It is possible to locate the position of the tremor with reasonable accuracy. Today the resolution is ± 24 m. This should be decreased to ± 5 m or less, which can be made by improvements of the recording equipment.

Discussion on Papers 13 and 14

DR C.D.V. WILSON (Liverpool University): Would Dr Westbrook comment on the type(s) of focal mechanism that he thinks might account for the dilational first motions that he has found for some of the tremors?

DR WESTBROOK (Paer 13): This is problematical, but currently I consider that the two most likely causes of focal mechanisms producing dilational first motions are collapse of strata into the goaf, probably with accompanying floor heave, and bed separation of competent strata above the goaf, just behind the working face.

DR B.O. SKIPP (Soil Mechanics Ltd, Bracknell): Was there any correlation between 'weights' in the mine and recorded tremors ('weights' being a mining term for a sudden onset of load on to the supports at the coal face)?

Has Dr Westbrook estimated ground motions at the epicentre?

DR WESTBROOK: We have investigated carefully correlations between 'weights' and tremors, because they appeared to be a likely cause of at least some of the tremors, this being particularly so for the first 'weight' on each panel. We found it difficult to do this, because the time at which a 'weight' occurs is not often recorded. There were, however, two occasions when tremors were associated with phenomena of a 'weight' type in the mine, but there were more known occasions when there was no correlation of a tremor with the occurrence of a 'weight'.

I have estimated the maximum vertical ground velocities in the epicentral region using the measured velocities at seismometer sites and have found that maximum values generally do not exceed 10 mm/s (given uncertainties of ground coupling values of 20 mm cannot be excluded). The larger tremors of 1975 were not included in the analysis because instrumental data was not available from them, but comparing the intensities estimated from the macroseismic survey for 15 July, 1975, carried out by Dr C.W.A. Browitt with that for a measured event in May 1976 it would appear quite likely that the maximum ground velocity for the 15 July event was about 60 mm/s. An array of seismometers established in the epicentral region in March this year by Dr Kuszniir of Keele University should provide more accurate information on ground velocities.

MR W. MATHER (Nobel's Explosives Co.Ltd, Stevenston): Was there any evidence of subsidence immediately following the occurrence of a seismic event?

DR WESTBROOK: We were interested to know whether any finite permanent change in ground level could be associated with any tremors. This would have required continuous measurement of height at several stations, and, unfortunately, we were unable to obtain any instruments capable of doing this.

MR D.B. O'NEILL (Crockett and Associate, Carshalton): In order to improve reliability of the tape loop delay system, could not a magnetic disc delay system such as is used in delayed speech reinforcement systems be employed?

MR STENLING (Paer 14): In principle it may be possible to use a magnetic disc delay system as suggested. It would, however, require a considerable redesign of the system. Normally, this type of system is designed for 1-4 channels. In our case we need 6-12 channels.

Also, the suggested system is designed for a limited frequency range, say 20-10 000 Hz direct recording. As we need a much better response at the lower frequencies, say down to at least 5 Hz, the system must be rebuilt for FM recording. The upper frequency limit represents no problem.

The suggested system is interesting, and further investigations will be carried out in order to gain full knowledge.

MR I.P. HAIGH (Sir Alexander Gibb and Partners, Reading): Could the meeting have a second look at Dr Westbrook's last slide, please?

DR WESTBROOK: The slide (Fig.1) shows the position of the tremor foci in a vertical north-south section. At each focus three arrows indicate the direction in which seismic waves have left the focus to arrive at three stations approximately in line with the section. The sense of the arrows indicates whether the first motion of the ground in that direction has been compressional or dilational.

MR K. FULLARD (Central Electricity Generating Board, Berkeley Nuclear Laboratories): With regard to the Stoke earth tremors, has it been possible to establish local attenuation laws?

DR WESTBROOK: I have not tried to independently

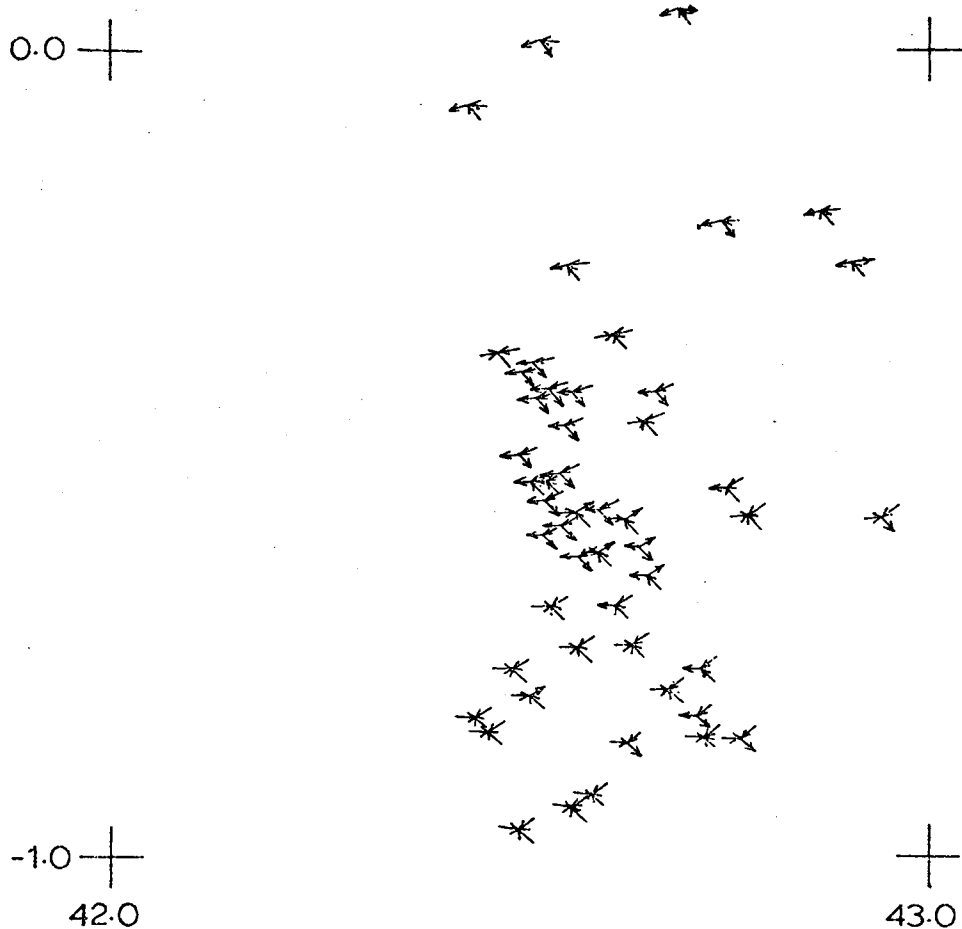


Fig.1. Position of tremor foci in a vertical north-south section

derive attenuation laws but have treated the signals according to established seismic theory assuming that geometrical spreading for surface waves was inversely proportional to distance and for body waves was inversely proportional to distance squared. Absorption was taken to be given by $e^{-\alpha x}$ where x is the distance travelled and α

is the absorption coefficient for any particular wavelength. The value used for α at 12 Hz was 0.24; derived from studying the relative amplitudes of signals at the different stations. This was complicated by different ground coupling at the stations.

15. Effects of vibrations on buildings and on occupants of buildings

H. SPLITTGERBER, Dr-Ing (Landesanstalt für Immissionsschutz, Essen)

The transmission conditions between a vibration source in the ground and a building are considered and some transfer factors obtained by field-testing are presented. Some effects in regard to the evaluation of vibration on occupants of buildings and on the building structure are described. Reference is made to recommendations which are discussed in the International Organization for Standardization.

INTRODUCTION

1. Because of increasing motorization and industrialization and decreasing distances to habitation areas the environmental protection against noise and vibration is of increasing importance. Vibration in buildings can interfere and affect the occupants of buildings in many ways. The quality of life can be reduced as also can working efficiency. Damage of the building construction can occur. Manmade vibrations such as caused by forging-hammers, presses, stationary machines, traffic, blastings etc. often are only of relevance within a relatively small distance from the source that is up to about some 100 m. If vibration in buildings occur there are mainly two effects to distinguish, the effect on occupants of buildings and the effect on the construction or parts of it. It seems impossible to evaluate the intensity of perceptible vibrations by subjective statements of people. Therefore vibration in buildings have to be measured objectively that means in a reproducible manner with measuring devices.

Transfer conditions

2. The transfer problem of vibrations between a source in the ground and a building can be explained as shown in Fig. 1. Some special points of the system are indicated in this Figure. It is an essential engineering task to evaluate the transfer functions f_j . In general this is very complicated.

3. Measurements of vibrations caused by quarry blasting and by forging-hammers were performed simultaneously outside in some distance of the building on the ground (point O) and at the foundation (point F). At 1...2 story brickwork dwelling-houses founded on soil such as sand, gravel or else the transfer factor $\Psi(F-O)$ of the velocity-amplitudes $\dot{\phi}_z(\max)$ was evaluated to

$$\Psi(F-O) = \frac{\dot{\phi}_z(F)}{\dot{\phi}_z(O)} = 0.9 \dots 0.3 \quad (1)$$

Index z indicates the vertical direction. The mean value is suggested to be about 0,5. Available data are not sufficient to estimate the confidence intervall with statistical methods.

4. Vibrations caused by quarry blasting were measured simultaneously on floors (point P) and at the foundation (point F). At 40 different floors (wooden beam and concrete construction) the transfer factors $\Psi(P-F)$ were

evaluated for about 80 blastings. The mean value was determined to

$$\bar{\Psi}(P-F) = \frac{\dot{\phi}_z(P)}{\dot{\phi}_z(F)} = 4,5 \quad (2)$$

$$s_{\bar{\Psi}} = 0,8 \text{ (standard deviation)}$$

$$\Psi(P-F) = 1,1 \dots 12,4 \text{ (range of all values)} \quad (3)$$

5. Inside the housing space a further transmission from the floor to pieces of furniture occurs. In Fig. 2 an example for vibration records measured at several points in a housing space is represented. The results are shown in Fig. 3. In this case there were measured greater velocity-amplitudes on the chair and the table than on the floor. The transfer factor is as it is in other cases, too, dependent on the mass, stiffness and damping conditions of the regarded mechanical system and on the exciting frequency.

6. Regarding the effect of vibration on man in buildings, it is necessary to consider that there is a further transmission factor between the pieces of furniture and the human body.

EVALUATION OF THE VIBRATION EFFECTS ON OCCUPANTS OF BUILDINGS

7. General. In this relation it is to differentiate between the physical properties of the system concerned, such as acceleration velocity, displacement, frequencies, the direction of vibration, duration (exposure time) and the human perception of vibration. On the basis of psychological experiments on whole body vibrations it was possible to propose equal sensation contours, see e.g. the publication of Jones and Saunders (ref. 1) and the references given in this paper. Thereupon in national and international standards contours for equal sensation were presented (ref. 2, 3). The IS 2631 defines and gives numerical values for limits of exposure for vibrations transmitted to the human body in the frequency range 1 to 80 Hz. The standard deals with both horizontal and vertical vibration transmitted to a standing or seating man along the body axis (x axis: foot-to-head; x axis: back-to-chest; y axis: right-to-left-side). The data upon which the limits are based come mainly from studies on aircraft pilots and drivers. These limits may not be very significant in the evaluation of disturbance due to building vibrations in private homes, offices etc.. A working group of the ISO/TC 108/ SC 4 has put forward a recommendation which shall be published as

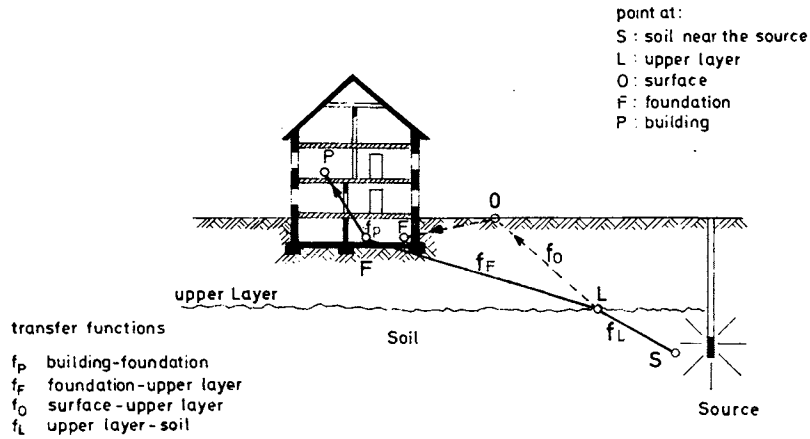


Fig.1. Transfer functions f_j concerning the system comprising source, soil, upper layer, foundation and building

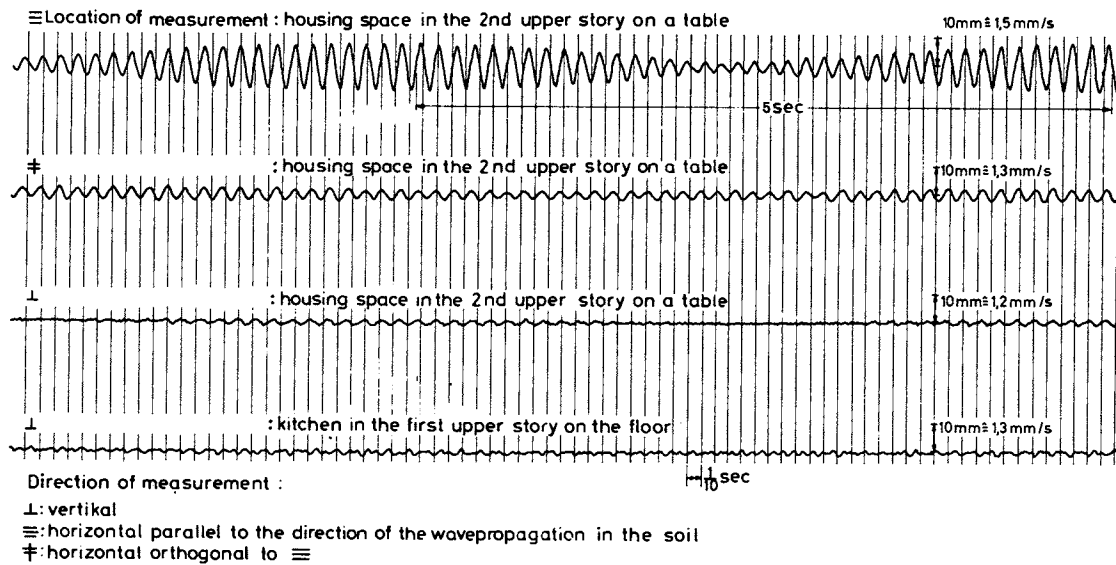


Fig.2. Example for measurements of steady-state vibrations: excitation - two heavy diesel engines (horizontal cylinder), $f_E=4$ cycles/sec

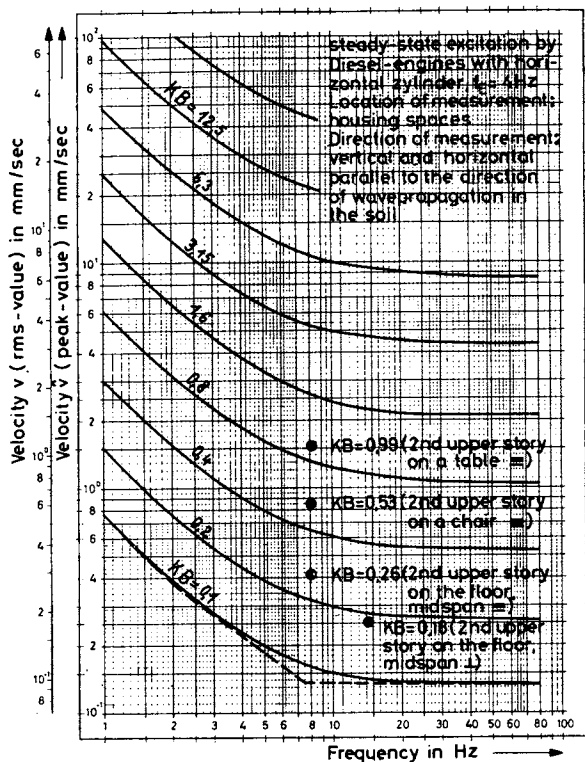


Fig.3. Results of measurements in velocity-frequency diagram and contours with equal KB-values according German Standard DIN 4150, part 2 (1975)

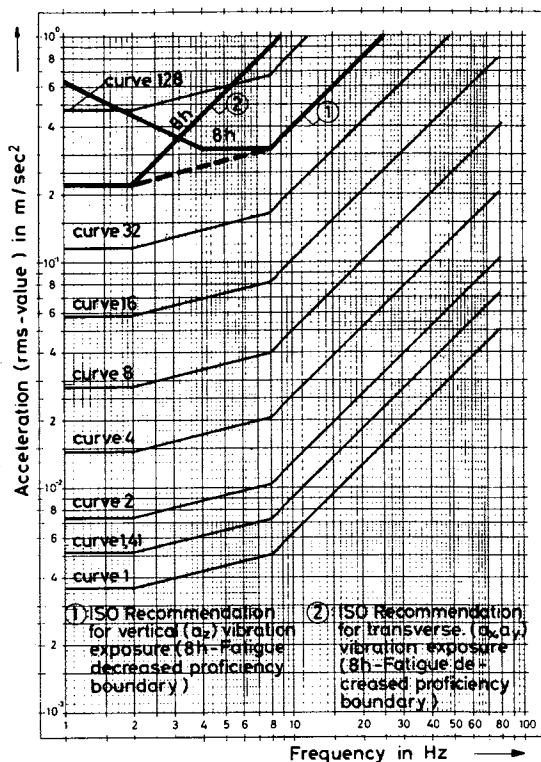


Fig.4. Combined standard (worst case combination of both z axis and x and y axis conditions) according Addendum 2 of ISO/IS 2631-1974

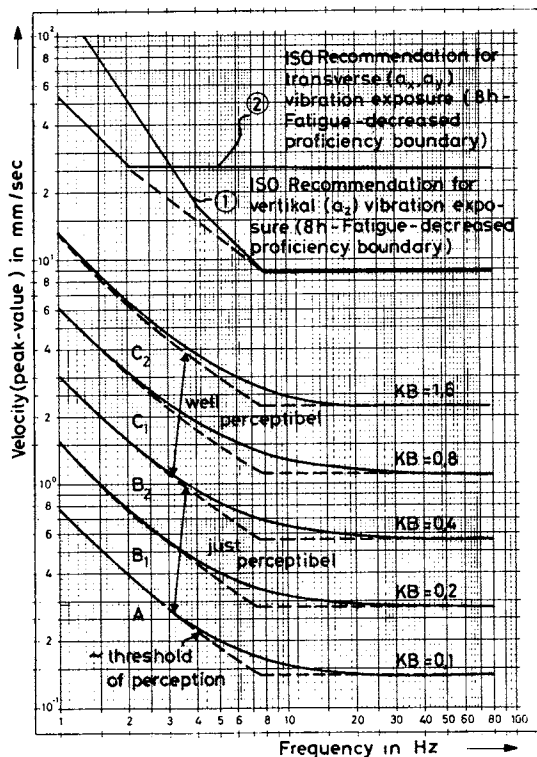


Fig.5. Weighting curves (curves with equal KB-values) according German VDI-guideline 2057, part 2, draft, 1976 and DIN 4150, part 2, 1975

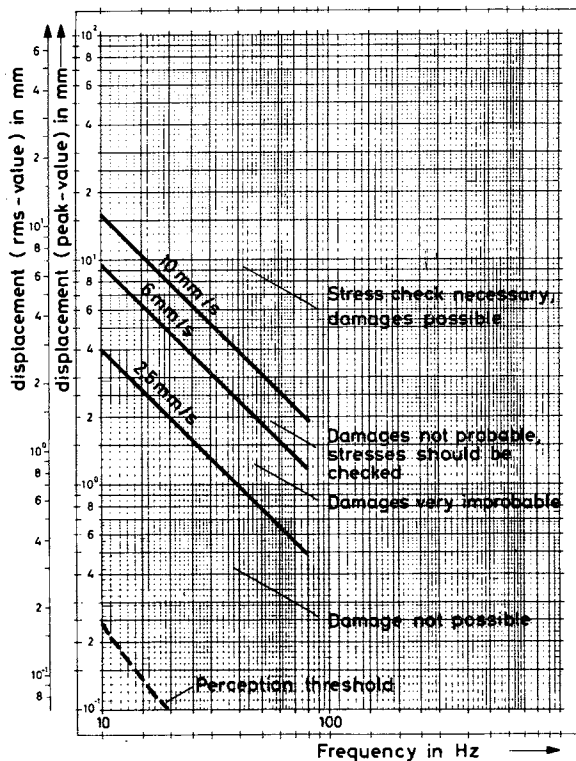


Fig.6. Rough evaluation of stationary floor vibrations by measurement of amplitude and frequency of vibration displacement

Place	Time	Continuous or Intermittent Vibration & Repeated Impulsive Shock	Impulsive Shock Excitation with not more than 3 Occurences per day
Hospital operating theatre & critical working areas	Day	1	1
	Night	1	1
Residential (minimum complaint level)	Day	2	16
	Night	1.41	1.41
Office	Day	4	128
	Night	4	128
Workshop	Day	8	128
	Night	8	128

Note

The figures given for continuous and intermittent vibration, together with repeated impulsive shock for residential, office and work shop areas, represent good environmental standards. If vibration levels are increased beyond these levels by a factor of up to two, there will be moderate complaint, and an increase by a factor of up to four will lead to mayor complaint.

Table 1. Weighting factors for acceptable building vibration. Factors are applied to basic level of Curve 1₆ which represents a rms velocity of $3.56 \times 10^{-3} \text{m/s}$ above 8 Hz, an acceleration of $5 \times 10^{-3} \text{m/s}^2$ at 8 Hz and an acceleration of $3.6 \times 10^{-3} \text{m/s}^2$ below 2 Hz

Category of Damage	Range v_R in mm/s onset of damage
Threshold damage	3...5
Minor damage	5...30
Mayor damage	> 100

Note

These values are based on measured foundation vibration in the frequency range from about 3 Hz to 100 Hz.

Table 2. Limiting values of vibration velocity v_R caused by quarry-blasting vibration in dwellings and offices in good physical condition

an addendum to IS 2631 (ref. 4). In this document a combined standard is considered as convenient because a building may be used for many different activities, standing, sitting and lying may all occur. This combined standard is represented in Fig. 4.

8. In German guidelines and a provisional standard so called KB-values are used for the evaluation (ref. 3, 5). The contours with equal KB-values are nearly in complete agreement with the combined standard according to the ISO-addendum (ref. 4). In Fig. 5 the relation is represented. The instantaneous perception is described in steps as not perceptible, just perceptible, well perceptible etc..

9. Acceptable Limits. Occupants of buildings can be annoyed by vibrations. Therefore unavoidable continuous vibration in residential buildings should be below or only slightly above the threshold of perception (ref. 6). In many countries evidence exists that there will be complaint if vibrations are only slightly above the threshold of perception (ref. 7, 8). Further the classification of buildings and building areas and the daytime is to consider. These criteria are derived from the human reaction to vibration. In the home and for continuous vibration the highest standards are required. Table 1 presents the weighting-factors which are in discussion in the ISO-addendum (ref. 4). Regulations and guidelines in several countries are in relatively good agreement with these recommendations.

10. Measurement of vibration should be taken on the floor at the point of greatest amplitude, commonly found at mid-span. Measurement should be taken along the three orthogonal axis and reference made to the appropriate human axis. Alternatively the combined standard could be considered in relation to the worst case found. The measuring point commonly is not the point of entry into the human body as it is taken e.g. in the automobil environment.

11. Instrumentation. For vibration measurement in buildings seismic pickups are used, preferably velocity pickups. Only in special cases displacement or acceleration pickups are employed. The vibration signals often are recorded as time-history. The physical quantity to be measured preferably is the particle velocity or from the velocity derived quantities, e.g. weighted with a filter to gain signals which are proportional to the KB-values.

EVALUATION OF THE VIBRATION EFFECTS ON BUILDINGS

12. For the evaluation of the effects of vibrations on buildings or on parts of it the dynamic loadings and anticipated number of loading cycles are important parameters. But for the probability of the occurrence of damages not only the magnitude of the vibration is of importance but other properties of the system, too, such as the soil, the foundation, the construction, the habit and age of the building etc.. As a consequence it seems to be difficult to establish reliable damage lines. Therefore it is to understand that all recommended vibration limits to avoid the risk of damage based on many field-investigations in many countries vary in a relatively wide range. The problem isn't solved satisfactory as yet. In spite of that a working group of the ISO is going to work on a guide to the measurement of vibration in buildings which should be employed in evaluation to mechanical vibration of

buildings. The purpose is to avoid exceeding the threshold damage. But it is uncertain whether it would be possible to recommend damage limits and gain the agreement of the majority of the member countries of the ISO.

13. In the draft now in discussion it is tried to describe several phases of damage which can occur, namely threshold damage, minor and major damage. In the case of vibration caused by shock and quarry blasting and steady vibration of whole buildings the use of the planned recommendation is restricted to the frequency range from about 1 Hz to 100 Hz. In the case of steady vibrations of parts of a building especially floor and wall vibrations it is restricted from about 10 Hz to 100 Hz.

14. In the case of vibration caused by shock and blasting the measuring quantity is the particle velocity v_p measured on the foundation of the building. The v_R -value is to be calculated from the instantaneous components of the vibration $v_x(t)$, $v_y(t)$ and $v_z(t)$ where the indices refer to the horizontal and vertical directions of a right hand set of orthogonal axis according the equation

$$v_R = \left| \sqrt{v_z^2(t) + v_x^2(t) + v_y^2(t)} \right|_{\max} \quad (4)$$

15. For blasting caused vibrations in residential property in good physical condition limiting values for particle velocity v_p presented in Table 2 are under consideration. In the range between 30 mm/sec and 100 mm/sec data available are not sufficient to define the nature of damage without regard to the condition, type of structure and foundation.

16. Steady vibration of parts of a building. For vibration of building parts, such as floors, dynamic stresses can be determined by means of statics using for example the displacement response mode and the frequency from measurements. The stresses in beams or plates vibrating close to resonance can be calculated from measurement of velocity or displacement and frequency if the measurement is performed at the points of maximum displacements (ref. 10). A rough evaluation of vibrations of stationary floor vibrations are presented in Fig. 6. This evaluation is also under discussion (ref. 9).

17. Horizontal vibration of the whole building. The real system of a building can be modeled using the vertical beam with one elastical built-in end and lumped masses (ref. 11) as a first approximation to estimate dynamic stresses, see Fig. 7. Above the ground surface the reaction of the inertia forces only act as additional loading on the system. It is

$$K_i = - a_i \hat{q}_i \quad (5)$$

In this equation \hat{q}_i means the acceleration and a_i the mass at the point i . After estimation of the cross-sectional areas of the loaded walls it is possible to determine especially the shear stresses as average values. Shear stresses often are the critical strain of the system.

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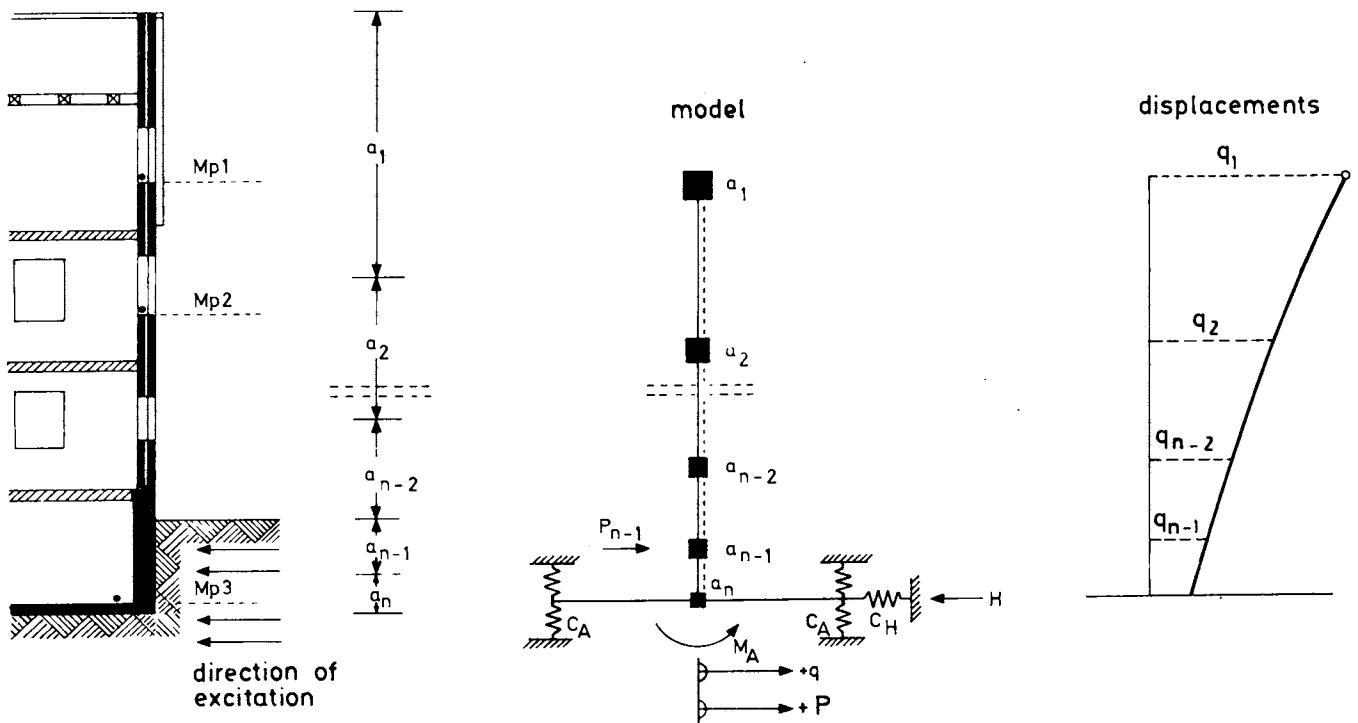


Fig.7. Real system, model and deformation line for horizontal vibration

16. Proposed international standards concerning vibration in buildings

C.ASHLEY, PhD BSc MIMechE (Bostrom Division, UOP Ltd, Northampton)

An International Standard on acceptable levels of vibration in buildings, with respect to the tolerance of humans, is very near its final stage. In order to acquaint a wider range of persons with its contents, it is reprinted in full and comment is made upon various aspects. In general it is concluded that the proposed Standard represents a reasonable compromise based upon current knowledge.

INTRODUCTION

1. For some considerable time a committee of the International Standards Organisation has worked on a new International Standard (ref.1) concerning vibration and man. This has now been published as International Standard 2631, "Guide for the Evaluation of Human Exposure to Whole Body Vibration". It was proposed that a series of amendments should be published as additions to the Standard to give guidance on vibration levels for particular circumstances. One of these first amendments (ref.2) is now on circulation for voting amongst member countries, and is likely, if approved, to become an International Standard. All too often in the past International Standards have not had sufficient circulation at the draft stage. Following discussions with the British Standards Institution it is proposed in this case to publish the full text, so that as wide a cross section of potential users as possible can have the opportunity to comment.

2. The author has been concerned with the drafting of this amendment, and in this paper it is possible to give some information on the background. The amendment has also been related to some national proposals prepared by Japan and the U.S.S.R.

3. The proposed amendment is given in the appendix and the following comments should be read in conjunction with the proposed amendment.

INTRODUCTION AND SCOPE OF APPENDIX

4. The appendix is only concerned with subjective response to vibration and does not take damage directly into account. Although it could be made more detailed by dealing with many more particular circumstances, it was felt simpler to restrict the examples and leave it to the common sense of the user.

MEASUREMENT OF VIBRATION

5. The key to the application of the Standard is obviously the sensible and economic means for measuring vibration levels in buildings. Other experimental work has shown that instrumentation

designed for the measurement of steady state vibration is often completely unsuited to the measurement of transient conditions. The frequency response necessary for transient vibration measurement is much wider than that necessary for steady state. Fortunately vibration frequencies in buildings are rarely below 10 Hz, so a system capable of dealing in a steady state sense with down to 2 Hz is probably adequate. Provided accurate answers are obtained, there is no particular preference for velocity or acceleration measurement. The Standard was written in terms of acceleration because the original document 2631 uses acceleration as the main parameter.

6. It is often desirable to carry out a frequency analysis of the vibration to identify the key frequency. When 2631 was being drafted, the current range of fixed narrow band width spectrum analysers was not commonly available, and hence third octave analysis was preferred. Currently either method would be suitable. For overall assessment only the root mean square value should be considered in relation to the Standard for guidance as to the acceptability of the vibration.

7. One of the reasons for drafting the combined Standard was to give a means whereby simple low cost instrumentation could be made available as widely as possible. The combined Standard can be accurately approximated by a single pole inverse filter with a transfer function as given in the Standard. This could be adapted for use in conjunction with either an accelerometer or velocity transducer. It is to be hoped that some simple type of portable meter could be developed on this basis, possibly as an adaptation of the sound level meters currently used extensively by local authorities and Health and Safety Officers.

ACCEPTABLE LIMITS AND THEIR DERIVATION

8. The fundamental level of the proposed Standard corresponding to level 1 was set by known research work on perception of vibration. Typically the level for the domestic home by

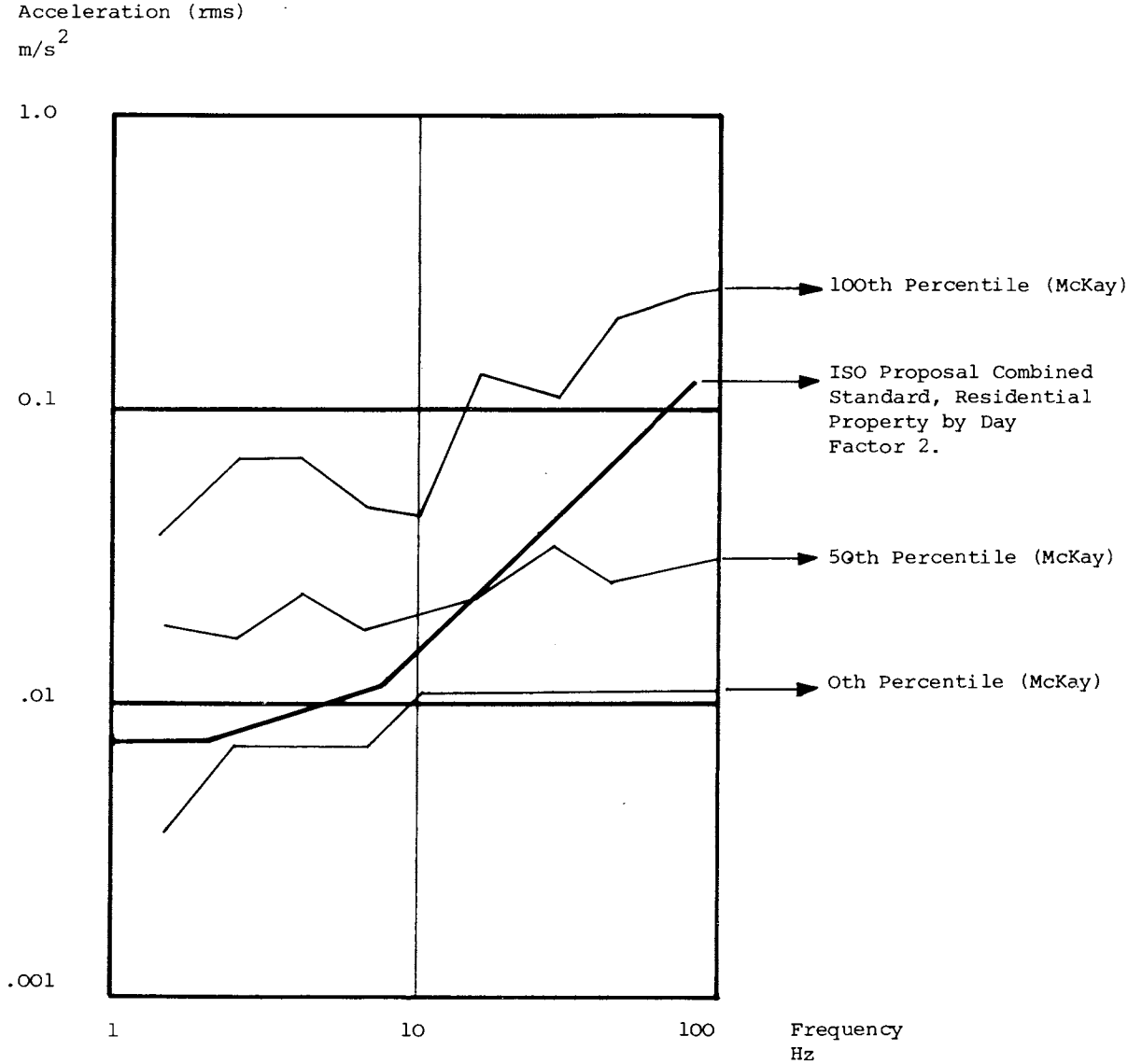


Fig.1. Proposed ISO Standard for continued vibration at level 2 (residential property by day) compared with the threshold of perception determined by McKay

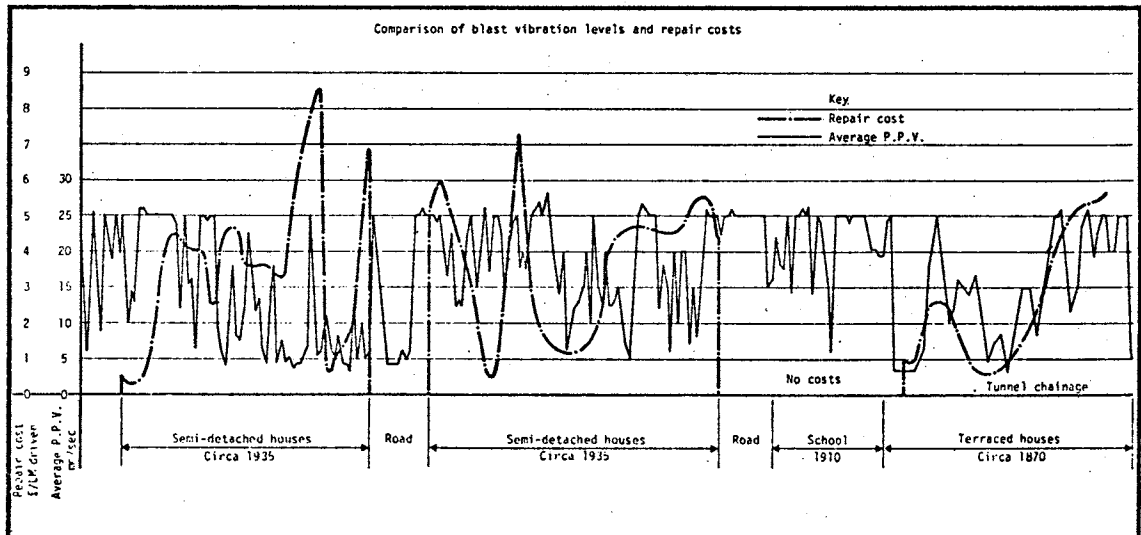


Fig.2. Comparison of peak foundation particle velocity generated by blasting with repair costs to buildings

day is set at level 2, which is within 1.0 db of a K value of 0.2 derived according to German Standard VDI 2057 (ref.3). More recent work by Dr. McKay (ref.4) at the University of Southampton on perception levels differs somewhat from the earlier work and is probably better based. The results of McKay are shown in Figure 1 compared with the proposed combined Standard at level 2. It will be noted that at around 20 Hz, which is a typical figure in building vibration, the average level of perception coincides with the proposed Standard for residential property by day.

9. The shape of the combined Standard is derived from 2631 and is fundamental to that document. To change the appendix to fit more closely to McKay's later work would also involve changing the base document IS 2631. This could take several years and for the moment the proposed levels seem reasonable.

IMPULSIVE SHOCK AND DAMAGE CRITERIA

10. The highest level of impulsive shock with a factor of 128 corresponds to a peak particle velocity of 18mm/sec. Impulsive shock at this level could be generated by building operations or quarrying involving blasting. The maximum particle velocity for significant damage from isolated events to be avoided is probably around 70mm/sec. A review of the state of the art in 1970 has been published in a Building Research Station memorandum (ref.5). It should be noted that the level for continuous vibration would be considerably lower.

11. Recently an interesting investigation has been made by Ashley and Parkes (ref.6) of the effect of peak particle velocity upon damage to fairly old property. A tunnelling project in Wolverhampton, England, required the use of explosives, and a record was kept of the peak particle velocity for every explosive shot. The tunnelling was under an old part of the town including houses up to one hundred years old. From the collected data, a graph (Figure 2) has been drawn correlating cost of rectifying damage with maximum particle velocity. It can be seen that the maximum damage rate for 25mm/sec. particle velocity was only £9 per linear meter of tunnel. The repair policy was generous and much of the cost was on replacing rendering which was in a poor condition before the work was started. In the case of this project more than adequate warning was given to all house occupants before work commenced and the project did not cause any major disturbance or leave any ill feeling after it had been completed.

12. The draft Standard recommended level for private houses with a factor of 16 corresponds to a peak particle velocity of only 2½ mm/sec. This is far below the level at which much damage would occur, but it is possible that at this level there could be some complaints from house occupants if there were no warning beforehand.

NATIONAL RECOMMENDATIONS ON VIBRATION LEVELS 13. In Russia a USSR Standard (ref.7) was published in 1975 entitled "Health Norm on Permissible Vibration in Residential Buildings". For residential buildings by day the mean acceleration level in the 16 Hz octave band should not exceed 10^{-2} m/s². This corresponds almost exactly to level 2 of the ISO proposed Standard. In Japan the Environmental Agency (ref.8) is preparing legislation to regulate vibration pollution from industrial plants and construction work. The proposed level for residential buildings suggests that vibration should be below level 4 of the ISO proposal.

CONCLUSION

14. It would appear that the new International Standard has been set at reasonable levels and should get a high measure of agreement. However, without suitable instrumentation to be able to apply it, it would be a considerable period of time before the Standard became effective. Let us hope that this conference generates the necessary action so that the vibration health environment of people can be properly protected.

15. Your comments on the proposed Standard would be welcome and it may still be possible to take them into account.

16. This is also a suitable opportunity to acknowledge the scientific research which has gone into the effect of vibration on man, and the help given by many persons to the work of the International Standards Organisation.

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APPENDIX. VIBRATION AND SHOCK LIMITS FOR OCCUPANTS IN BUILDINGS: DRAFT AMENDMENT (JANUARY 1977) TO ISO STANDARD 2631-1974

0 Introduction

Vibration in buildings can interfere and affect the occupants in many ways. The quality of life can be reduced, as also can working efficiency. There are several national proposals for acceptable limits of vibration in buildings, but the time has now come for an International Standard to give unifying guidance to the sort of levels which are acceptable under different types of circumstances.

1 Scope of addendum

A Standard of this type has to take into account many factors. At present this addendum is limited to the following considerations:

- (1) type of excitation - for example transient (shock) and/or steady vibration;
- (2) usage of the occupied space in buildings - for example, hospital operating theatres, residential, offices and factories;
- (3) time of day;
- (4) limits of acceptability. In a proposal of this type there is no hard and fast line of acceptability, but guidance is given as to the level of complaint to be achieved at different levels of vibration. In cases where sensitive equipment or delicate operations impose more stringent limits than human comfort criteria, then the more stringent criteria should be applied.

2 Characteristics of building vibration

2.1 Direction of vibration

Because a building may be used for many different activities, standing, sitting and lying may all occur, hence vertical vibration of the building may enter the body as either Z axis, X axis or Y axis vibration, as shown in Figure 1. (The axes of vibration are those defined in ISO Standard 2631, Section 3.1.) The Standard is written for all three axes of vibration, and normally the measured vibration should be referred to the appropriate Standard. In cases where it is not clear which direction to apply, it is often more convenient to consider the combined Standard detailed in Section 3.4 below.

2.2 Random or multi-frequency vibration

Random or multi-frequency vibration represents a particular problem which fortunately does not often occur in buildings. IS 2631, Section 4.2, proposes both third octave and overall weighted vibration analyses. There is evidence from research concerning the building environment to suggest that there are interaction effects between different frequencies of vibration. Under these circumstances and for random vibration, an overall weighting method is to be preferred. A suitable weighting network for preliminary investigations would be that described in the note attached to Section 3.4 of this addendum.

2.3 The characterisation of impulsive shock and intermittent vibration

Continuous vibration of a repetitive nature is

easy to identify and classify. The borderline between impulsive shock and intermittent vibration is difficult to define. Impulsive shock is characterised by a rapid build-up to a peak followed by decay, and is typically excited in buildings by blasting, forging presses or pile driving using an impact device. Intermittent vibration may only last a few seconds, but is characterised by a build-up to a level which is maintained for a considerable number of cycles. Examples of this in buildings would be traffic excited vibration and vibration generated inside a building by machinery starting up or on intermittent service. Pile driving by modern methods using vibrating columns would also be classified as continuous or intermittent vibration and not as impulsive shock.

It is intended that impulsive shock created by forging presses or conventional pile drivers should be treated in a similar manner to continuous and intermittent vibration. Research has shown that vibration which only occurs at a specific instance, for example domestic building vibration generated by a passing bus, causes the same level of annoyance as continuous vibration.

Blasting which occurs only up to three times per day is a special case. It is a general recommendation that operations of this nature should never take place at night due to the disturbance. During the daytime they should be limited to a small number of occurrences. The levels of vibration generated due to blasting are of an order of magnitude greater than traffic and general building vibrations, and can only be accepted on the basis of very limited exposure.

2.4 Classification of buildings and building areas

The criteria of classification are derived from the human reaction to vibration. In the home the highest standards are required, and this is characterised by an absence of detectable vibration. Under other conditions, such as in offices and factories, there is some tolerance to vibration disturbance.

In this Standard no differentiation has been made between different types of residential area, ie city centre, urban or rural. It is considered that similar standards should be met for all occupants of residential property. Some types of areas have not been classified, ie restaurants or places of entertainment, but common sense suggests the most appropriate classification - for example standards in a restaurant should be similar to those in residential property. It should be noted that certain entertainment areas in long span buildings present particular problems from self-generated vibration, such as that from dancing.

Hospitals have not been given a higher standard in general because there is some evidence that patients prefer to be in touch to some extent with the outside world, but operating theatres and laboratories should be considered as critical areas.

2.5 Measurement of vibration

IS 2631 recommends the use of "root mean square" acceleration as the standard unit of measurement.

If possible, building vibration should be measured in acceleration terms, but in some cases it may be found necessary to measure in velocity or displacement. For these situations the vibration should be treated as sinusoidal and the appropriate correction factors, which are a function of frequency, used to transform either the measurement or the standard into compatible units.

In the case of impulsive vibration or shock the peak value of the velocity or acceleration is the preferred unit of measurement. A trace of the vibration should be obtained upon a suitable instrument and the peak level estimated. The motion should then be considered sinusoidal and the correction factors applied for the difference between peak and rms, and the frequency dependent factors used to transform either measurement or standard into compatible units.

If frequency analysis of the vibration is required, then IS 2631 recommends 3rd octave filters. In certain circumstances it may be useful to analyse the vibration in terms of narrow fixed band width filters in order to clearly identify resonant frequencies.

Measurement of vibration should be taken on the floor at the point of greatest amplitude, commonly found at mid-span. This should be close to the point of entry of vibration to the human subject. Measurement should be taken along the three orthogonal axes, and reference made to the appropriate human axis standard to determine whether limits have been exceeded. Alternatively the combined Standard could be considered in relation to the worst case found.

In the case of impulsive shock caused by blasting, measurement may be made at the foundations to check for structural damage. It is also necessary to measure according to the technique given above in the areas of human habitation.

3 Characterisation of building vibration and acceptable limits

3.1 Acceptable limits

All the following proposals are related to the recommendations for general vibration on humans given in IS 2631. The presentation of information is in the form of a basic rating which is given for the most stringent conditions. From this basic rating a multiplication factor is then applied according to the tables for other more permissive situations.

The lowest basic rating has been defined in the area of the threshold of human perception. It is based upon research work completed up to the end of 1975.

Experience has shown in many countries that complaints of building vibrations in residential situations are likely to arise from occupants if the vibration levels are only slightly in excess of perception levels. In general the limits are related to this acceptance by the occupants and are not determined by any other factors such as short-term health and working efficiency. Indeed the levels are such that there is no possibility of fatigue or other vibration-induced syndromes.

3.2 Foot to head ("Z" axis) vibration limits

For Z axis vibration the standard is shown in Figure 2. For frequencies between 4 Hz and 8 Hz the maximum acceleration (rms) is $5 \times 10^{-3} \text{m/s}^2$. At frequencies below 4 Hz the limit changes at 3 dB/octave. For frequencies greater than 8 Hz the limit increases by 6 dB/octave. For conditions other than the base shown by Curve 1 a series of weighting factors apply and these are given in Table 1. For example, for residential property the weighting factor is two, hence at 4 to 8 Hz the maximum permissible rms acceleration for residential property by day would be 10^{-2}m/s^2 .

3.3 Side to side or back to chest (X or Y axis) vibration limits

For X and Y axis human vibration a different base curve applies which is shown in Figure 3. For frequencies of 1-2 Hz a maximum acceleration level of $3.6 \times 10^{-3} \text{m/s}^2$ will apply. At frequencies higher than 2 Hz the acceptable acceleration level will increase at 6 dB/octave. This means that for frequencies greater than 2 Hz a maximum rms velocity limit applies.

It will be noted that the standard for X or Y axis vibration is more severe than the Z axis case at low frequencies. This is due to the sensitivity of the human body towards sway at these low frequencies.

The table of weighting factors given in Table 1 also applies to X or Y axis vibration.

3.4 Combined Standard - recommended limits for undefined axis of human vibration exposure

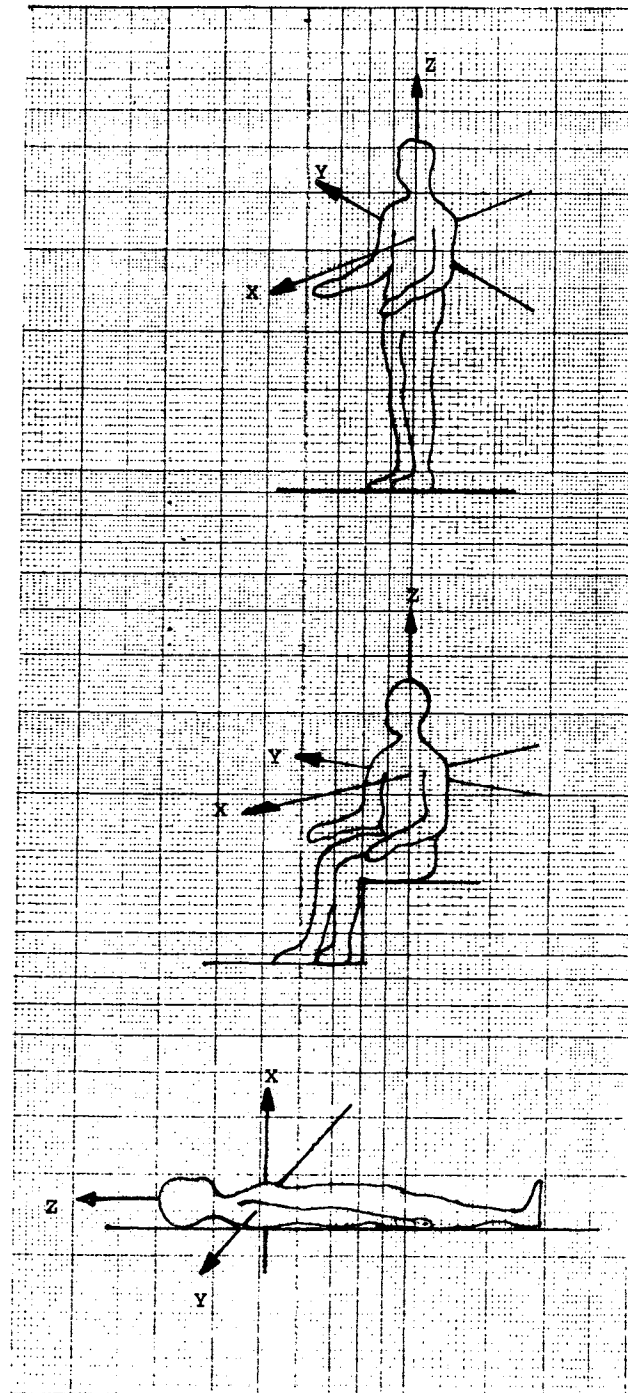
In many situations the same building area may be used in both the lying and standing positions at different times of the day. If this is the case, then a combined Standard using the worst case combination of both the Z axis and X and Y axis conditions should be applied. This combination curve is shown in Figure 4 and the same weighting factors given in Table 1 still apply.

This combined Standard could also be used for preliminary investigations to decide whether a vibration problem exists. In the case of combined or random vibrations the combined Standard could be approximated by a simple weighting function defined by the mathematical expression given below:

$$G(i\omega) = \frac{1}{1 + \frac{i\omega}{11.2\pi}}$$

where $G(i\omega)$ is the transmissibility of the filter, i represents the square route of -1 , ω represents the exciting frequency.

This mathematical expression defines an electronic weighting filter of the low pass type. At low frequencies the transmissibility is zero, and at high frequencies attenuation is at 6 dB/octave. The corner frequency is 5.6 Hz.



X axis = back to chest
Y axis = right side to left side
Z axis = foot (or buttocks) to head

Fig.1. Directions of co-ordinate systems for mechanical vibrations influencing humans

Table 1. Weighting factors for acceptable building vibration (factors applied to basic level of Curve 1 (Figs 2-4))

Place	Time	Continuous or intermittent vibration & repeated impulsive shock	Impulsive shock excitation with not more than 3 occurrences per day
Hospital operating theatre & critical working areas	Day	1	1
	Night	1	1
Residential (minimum complaint level)	Day	2 ³⁾	16
	Night	1.41	1.41
Office	Day	4 ³⁾	128
	Night	4	128
Workshop	Day	8 ³⁾	128
	Night	8	128

Note 1. Curve 1 for the simplified method represents a rms velocity of 0.995×10^{-4} m/s above 8 Hz, an acceleration of 5×10^{-3} m/s² at 8 Hz and an acceleration of 3.6×10^{-3} m/s² below 2 Hz. The rms velocity above 8 Hz corresponds for sinusoidal motion to a peak velocity of 1.41×10^{-3} m/s.

Note 2. Levels of acceptable impulsive shock in hospital operating theatres and critical working areas could be the same as in residential areas, provided there is due agreement and warning.

Note 3. The figures given for continuous and intermittent vibration, together with repeated

impulsive shock for residential, office and work shop areas, represent good environmental standards. If vibration levels are increased beyond these levels by a factor of up to two, there will be moderate complaint, and an increase by a factor of up to four will lead to major complaint.

Note 4. The levels for impulsive shock excitation occurring not more than three times per day in offices and work shop areas cannot be increased without some possibility of structural damage occurring, as well as a significant disruption of working activity.

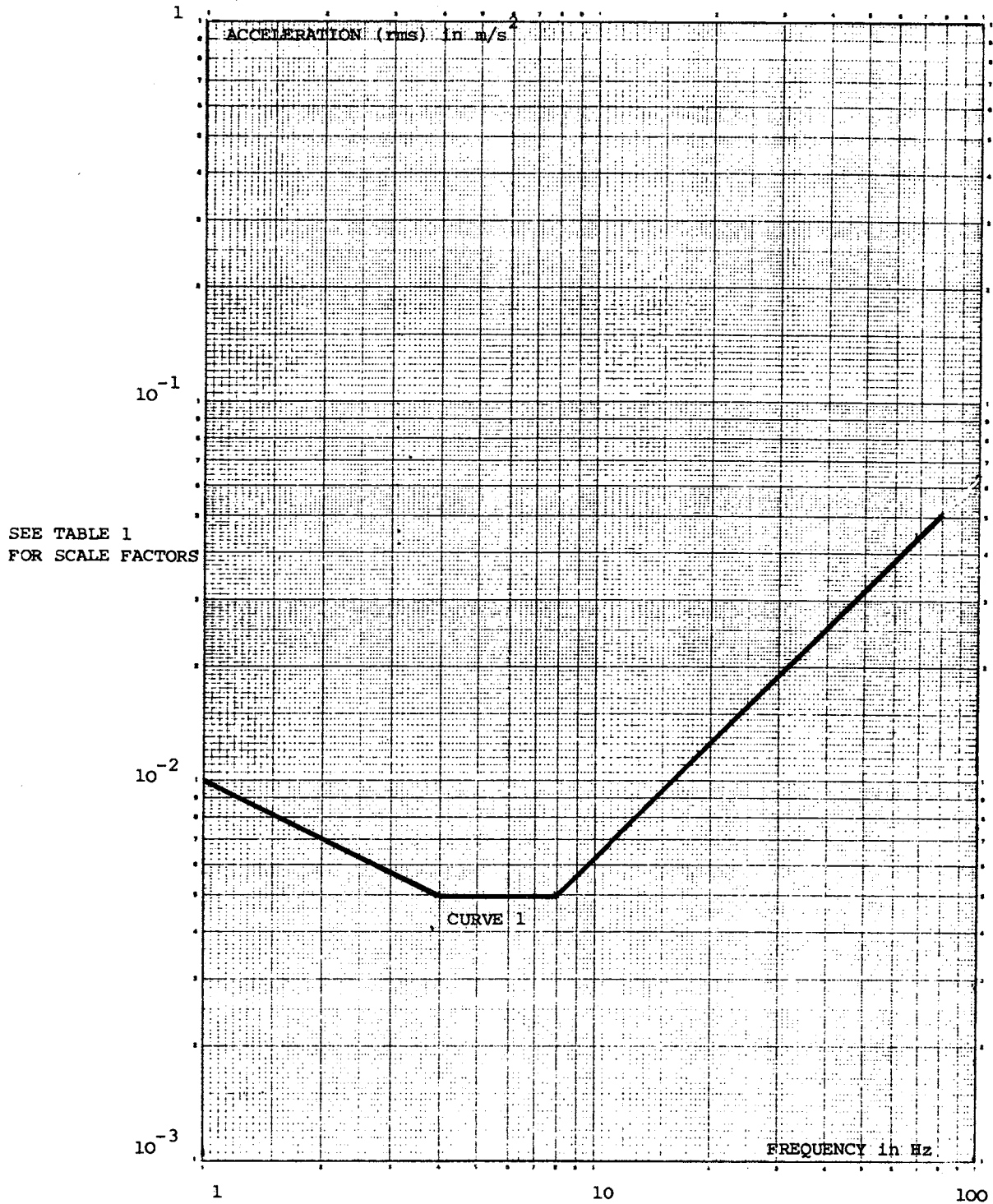


Fig.2. Building vibration Z axis limit (base curve for foot (or buttock) to head vibration limits, cf. Section 4)

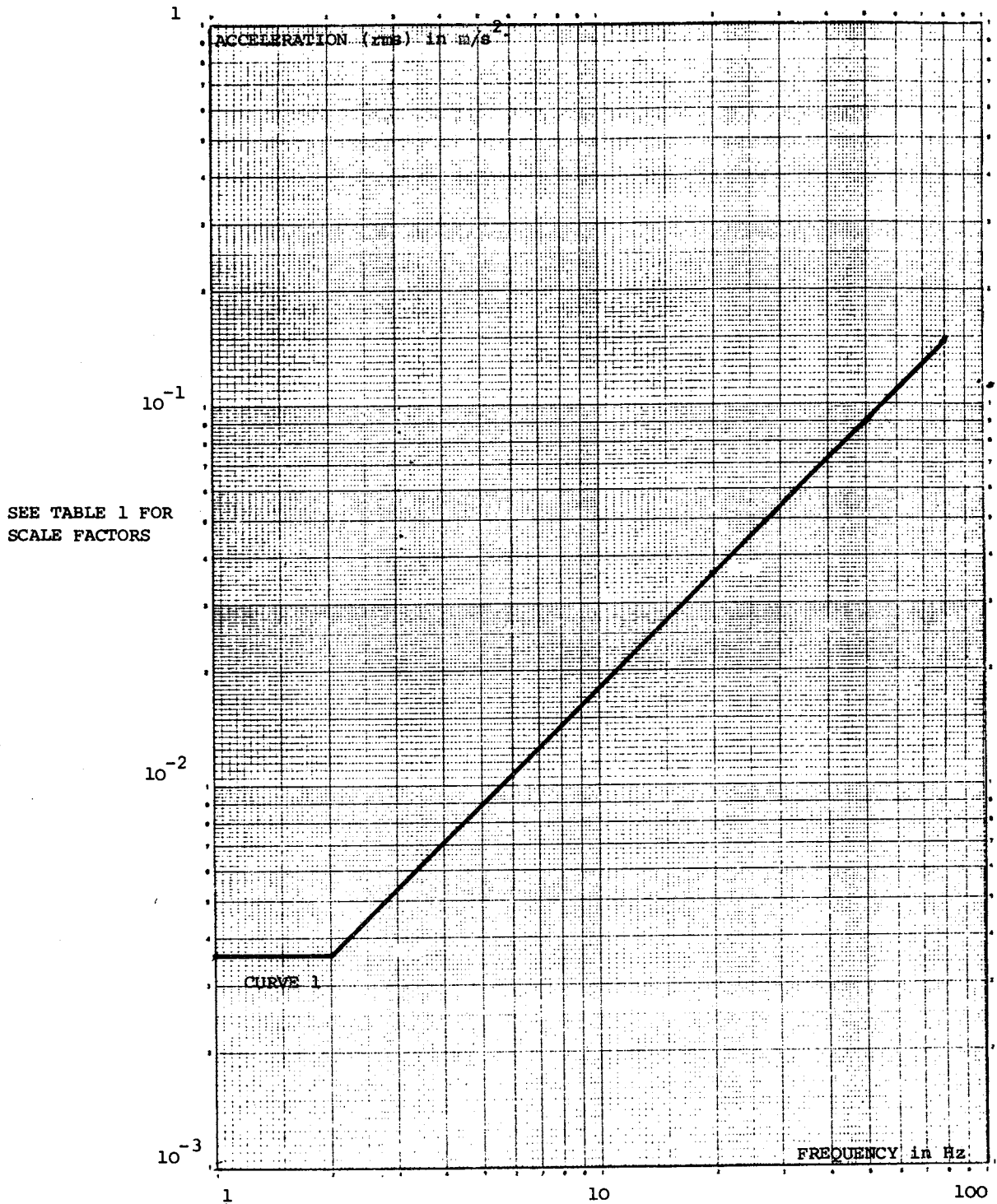


Fig.3. Building vibration X and Y axis limits (base curve for side to side and back to chest vibration limits for humans in building areas)

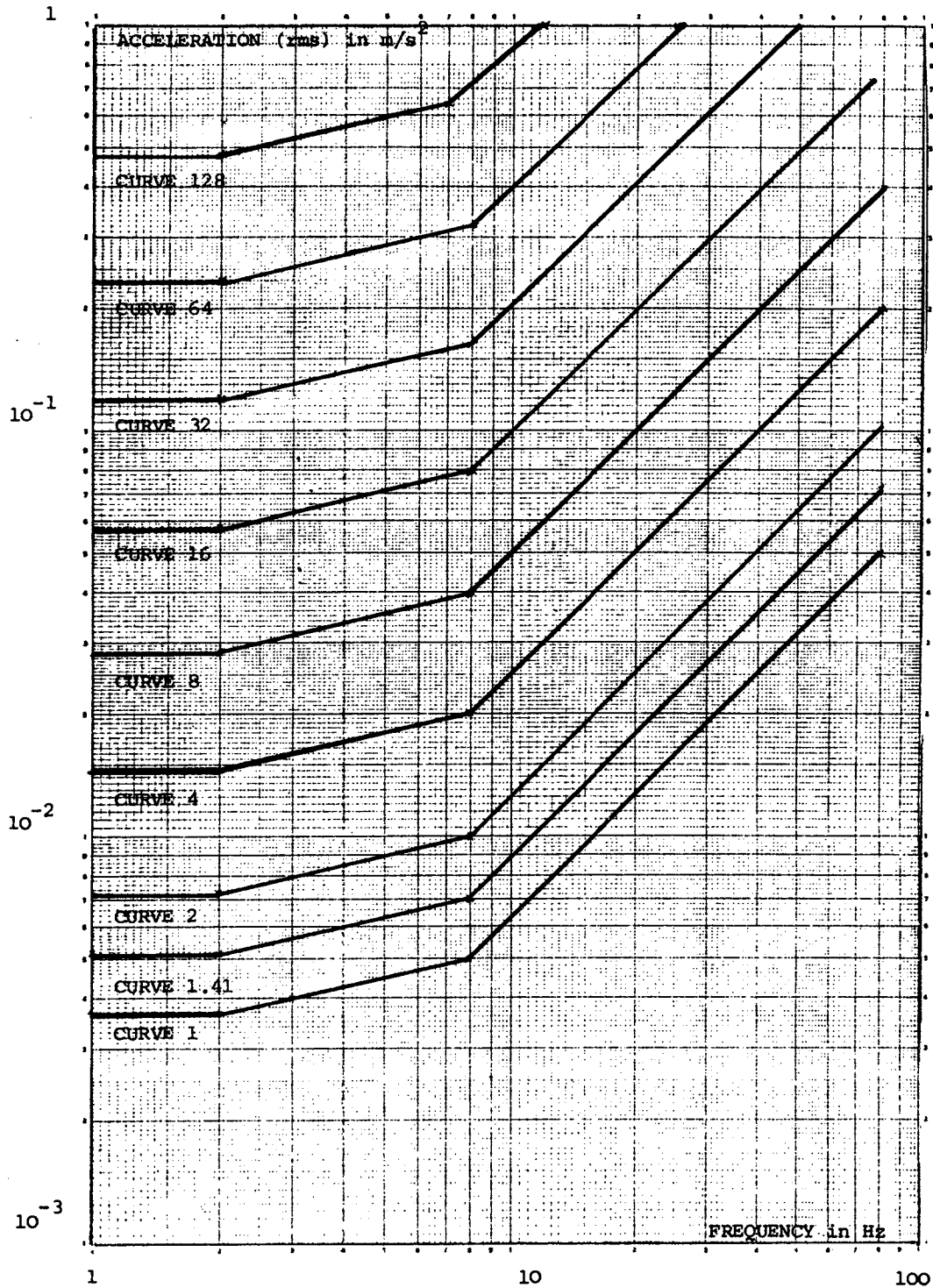


Fig.4. Vibration in buildings: combined Standard (combination of worst cases for all three axes); additional curves are shown corresponding to various correction factors according to Table 1

Discussion on Papers 15 and 16

DR SPLITTGERBER (Paper 15): In Paper 16, in relation to the threshold of perception, reference is made to recent work of McKay (reference 4 of paper). In Fig.1 of the paper are represented the average perception level and several percentiles in comparison with level 2 of the ISO standard.

Defining the threshold of perception is a statistical problem, indeed. Without regarding other parameters one would expect a probability distribution for the threshold of perception depending on the number and the tested persons; the group of it will always be restricted.

In order to define the threshold of perception about 70 persons especially in sitting posture were tested not on a shaking table but in the normal environment of an office in a building by exciting the floor with steady-state sinusoidal vibration.¹ The test room in our institute was installed with furniture as usual. The building is erected with prefabricated building parts and it was quite easy to excite the floor with a relatively small motor having an unbalanced weight of about 240 g. This motor was mounted in the room adjacent to the test room.

The results as cumulative frequency curves are presented in Figs 1 and 2. They are approximately of normal type (Gaussian distribution). The results are in good agreement with those of McKay. The average level (50th percentile) for example at 13 Hz (see Fig.1) was evaluated at peak particle velocities measured on the floor of $\hat{v} = 0.32$ mm/s. That corresponds with a K value of $K = 0.20$ and this value is nearly identical with the level 2 proposed in the addendum of the ISO standard.

In relation to frequency analysis of vibration signals, reference is made in Paper 16 to ISO Standard 2631. It is stated that for overall assessment only the root-mean-square value should be considered in relation to the standard for guidance as to the acceptability of the vibration.

In IS 2631, r.m.s. values, indeed, are the values to which particular preference is given. This is a widely used possibility to treat the problems if periodic and random vibrations are to be considered. But in the building environment often transient vibrations occur. Fig.3 presents as an example a velocity-time record. The vibrations were caused by forging hammers and measurements were made at the foundation and on floors in a nearby residential building. For such vibrations there arise problems in evaluat-

ing r.m.s. values. It seems that r.m.s. values do not apply adequately to non-stationary processes because there is no reasonable argument for defining the averaging time. If running integration is used the averaging time is not defined as yet for vibration signals. If weighted integration/averaging is used by measuring devices, a time-weighting effect of the signals is unavoidable, as for noise measurements. Further, by using weighted integration, r.m.s. values vary in time, and in order to obtain a single value to characterize the vibration it is necessary to define an adequate method for analysis.

DR ASHLEY (Paper 16): I am very pleased to receive additional data from Dr Splittgerber concerning threshold of perception. When ISO levels 1, 2 and 4 are superimposed, as shown in Figs 4 and 5, they correspond remarkably closely to the 5%, mean and 90th percentile case accordingly. This would suggest that level 4, which corresponds to a high level of complaint, also covers the perception of 95% of the population. This agrees with the original hypothesis that if the sensation of vibration is detectable in private property, it will lead to complaints.

The transient responses recorded on a building and shown in Fig.3 illustrate the difficulty of categorizing transient shock in mean terms. However, I think it is possible to analyse these traces, particularly those corresponding to the mid-span on the ground floor and first upper floor. If one considers the worst of the shock impulses, then a typical peak figure would be ± 1.4 mm/s at a frequency of 27 Hz. This peak is sustained for around 2 cycles of peak excitation. After translation into acceleration terms, this shows an r.m.s. value of 1.168 m/s². This corresponds to a level with a weighting factor of 10. It is suggested by the standard that the level of residential property for maximum complaint corresponds to a weighting factor of 8, hence one could assume that the vibration shown is in excess of the maximum complaint level. The case would obviously merit further investigation. However, this exercise in the interpretation of the standard does raise several questions.

- (a) Should the standard be more specific in giving guidance in how to categorize and deal with certain cases?
- (b) Would the standard be better if repeated impulsive shock was given primary importance

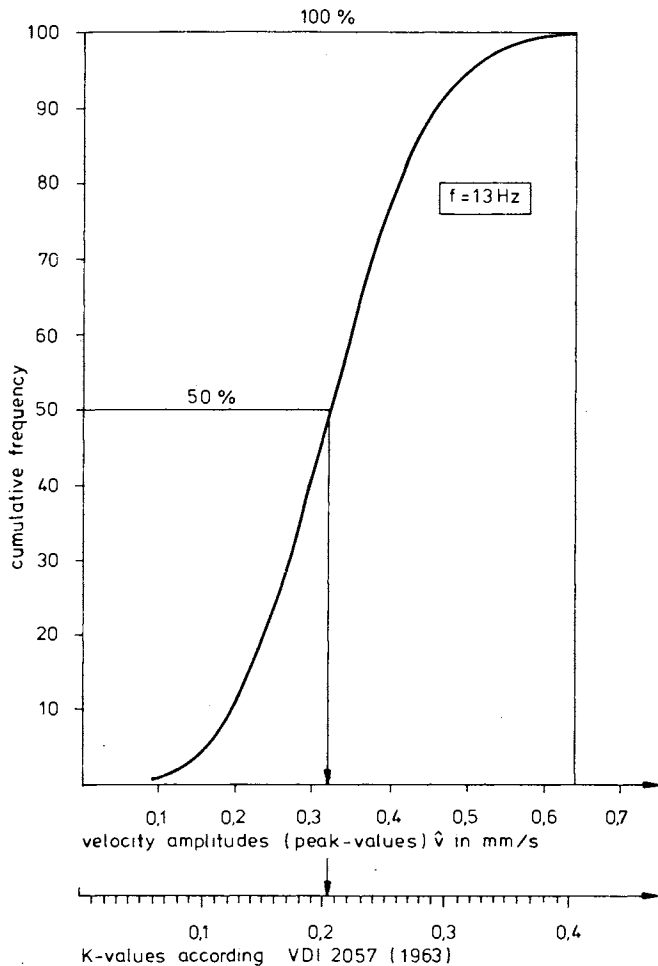


Fig. 1. Cumulative statistical distribution for the threshold of perception in sitting posture for vibration in vertical direction:¹ exciting frequency 13 Hz

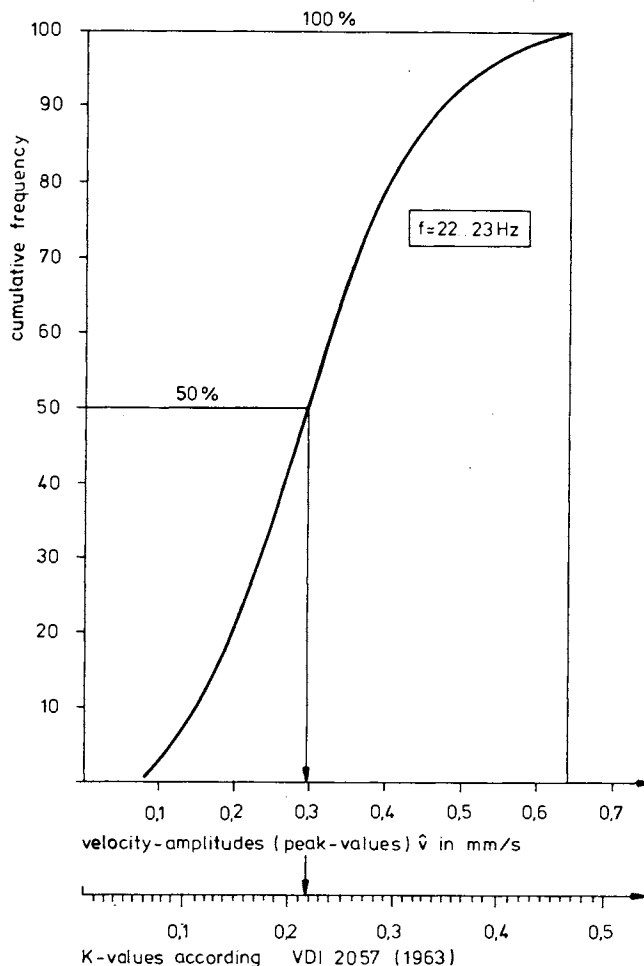


Fig. 2. Cumulative statistical distribution for the threshold of perception in sitting posture for vibration in vertical direction:¹ exciting frequency 22-23 Hz

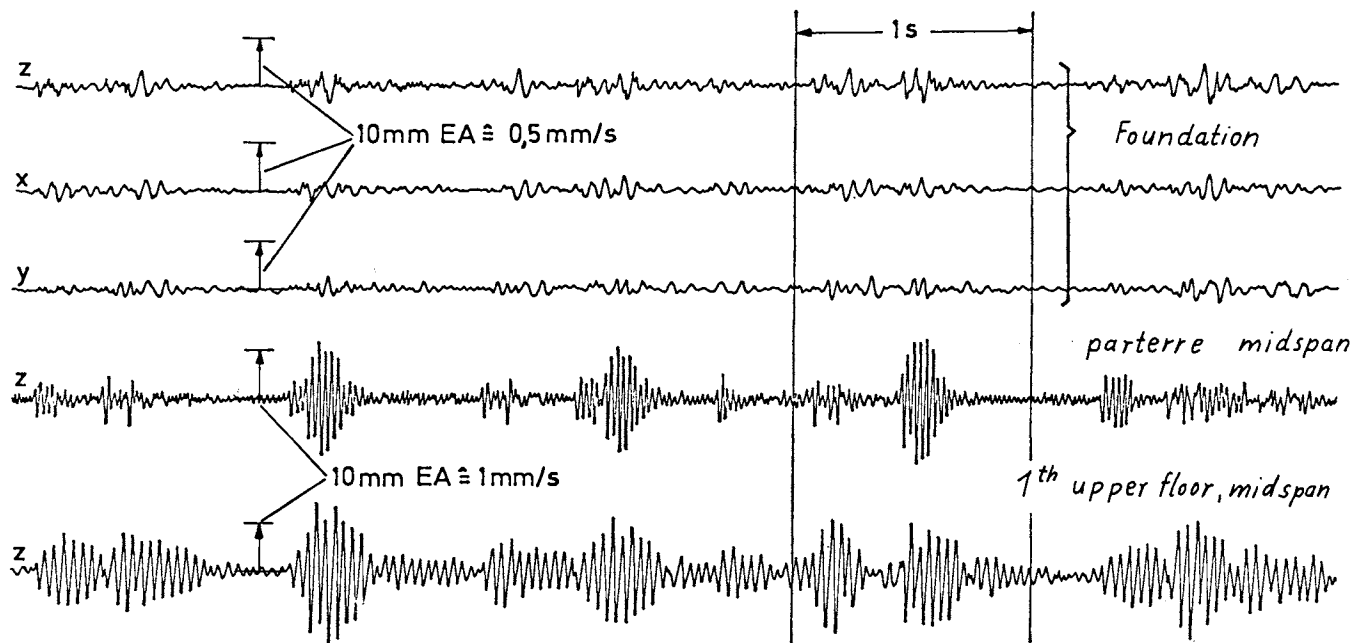


Fig. 3. Record of vibrations in a residential building caused by forging hammers nearby

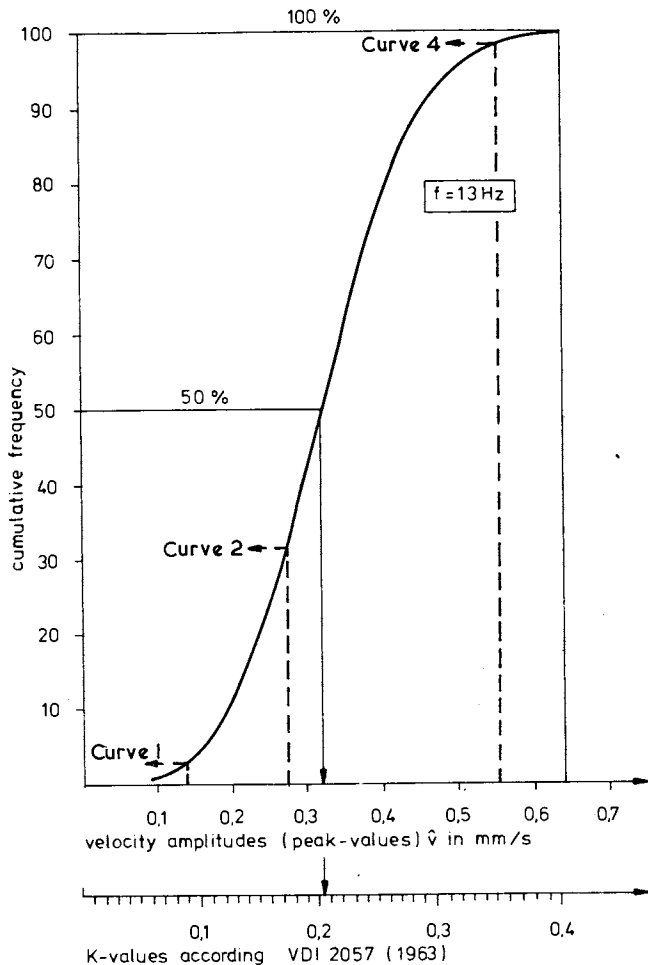


Fig.4. As Fig.1, with superimposition of the levels corresponding to weighting factors 1, 2 and 4 from the ISO amendment

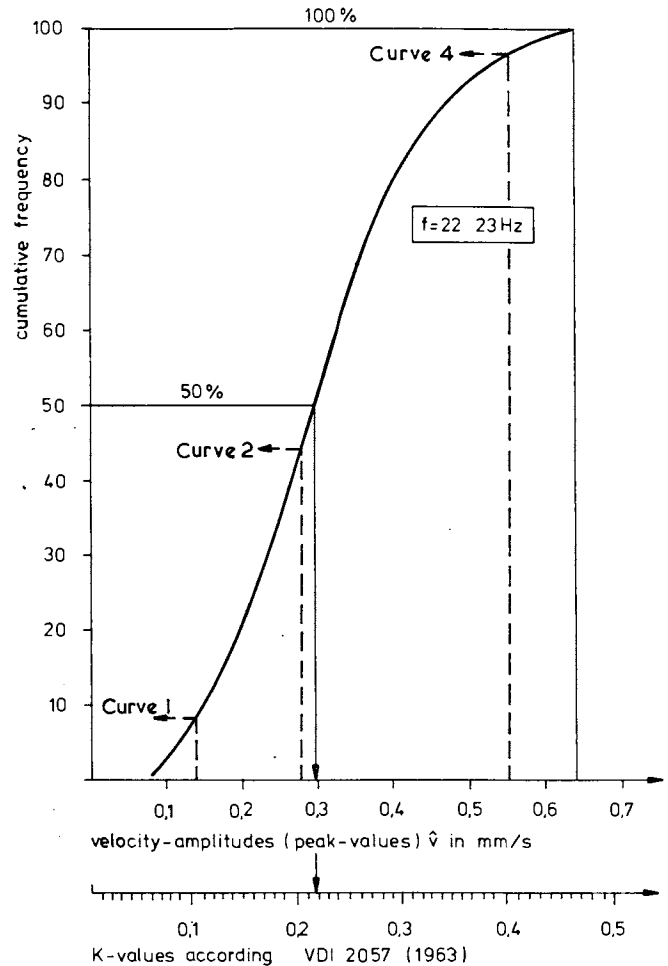


Fig.5. As Fig.2, with superimposition of the levels corresponding to weighting factors 1, 2 and 4 from the ISO amendment, showing that curve 2 corresponds to the 50 percentile of perception

in terms of peak velocity and not in terms of r.m.s. acceleration sustained over a few cycles?

(c) Measurement at the foundations gives a very erroneous impression compared with measurements at mid-span of the building.

DR P.L. WILLMORE (Institute of Geological Sciences, Edinburgh): In the discussion on Papers 1-4, we agreed on the dangers of basing peak-reading assumptions on instruments having sharp cut-offs at 1 Hz or higher. Equipment going down to much lower frequencies whilst retaining reasonable portability is available in the earthquake field. Flat response to velocity is extensible down to 1/50 Hz or so. Accelerometers working down to DC are available at sensitivity levels as low as $10^{-9}g$.

It should be noted that conventional peak/r.m.s. relationships are valid only for sinusoidal inputs. For impulsive inputs, nothing short of complete differentiation or integration processes will suffice for transformation between input parameters.

DR ASHLEY: I am glad to hear that equipment with an extended low frequency range is available for

seismographic measurements. I can do nothing but agree that for impulsive inputs nothing short of complete differentiation suffices.

DR B.O. SKIPP (Soil Mechanics Ltd, Bracknell): Dr Ashley has noted the prevalence of 4.5 Hz (strong motion seismograph) geophones. We have compared SMAI, piezo accelerometers and 4.5 Hz geophones responding to near impact and explosion. Integrating the acceleration records from quarry blasting at 1 km distance gave good agreement with peak particle velocity measured with geophones. Such concurrence was not found between the integrated acceleration as recorded by a strong motion accelerometer and the peak particle velocity recorded by geophones when measuring within 40 m of demolition impact.

DR ASHLEY: My own experience has been that velocity pick-ups with a natural frequency of 4-5 Hz give erroneous figures for transient shock inputs in the operation range of 20-100 mm/s. However, with calibration and using the peak to peak level recorded, a reasonable estimate could be made of the maximum level of single pulse transient vibration.

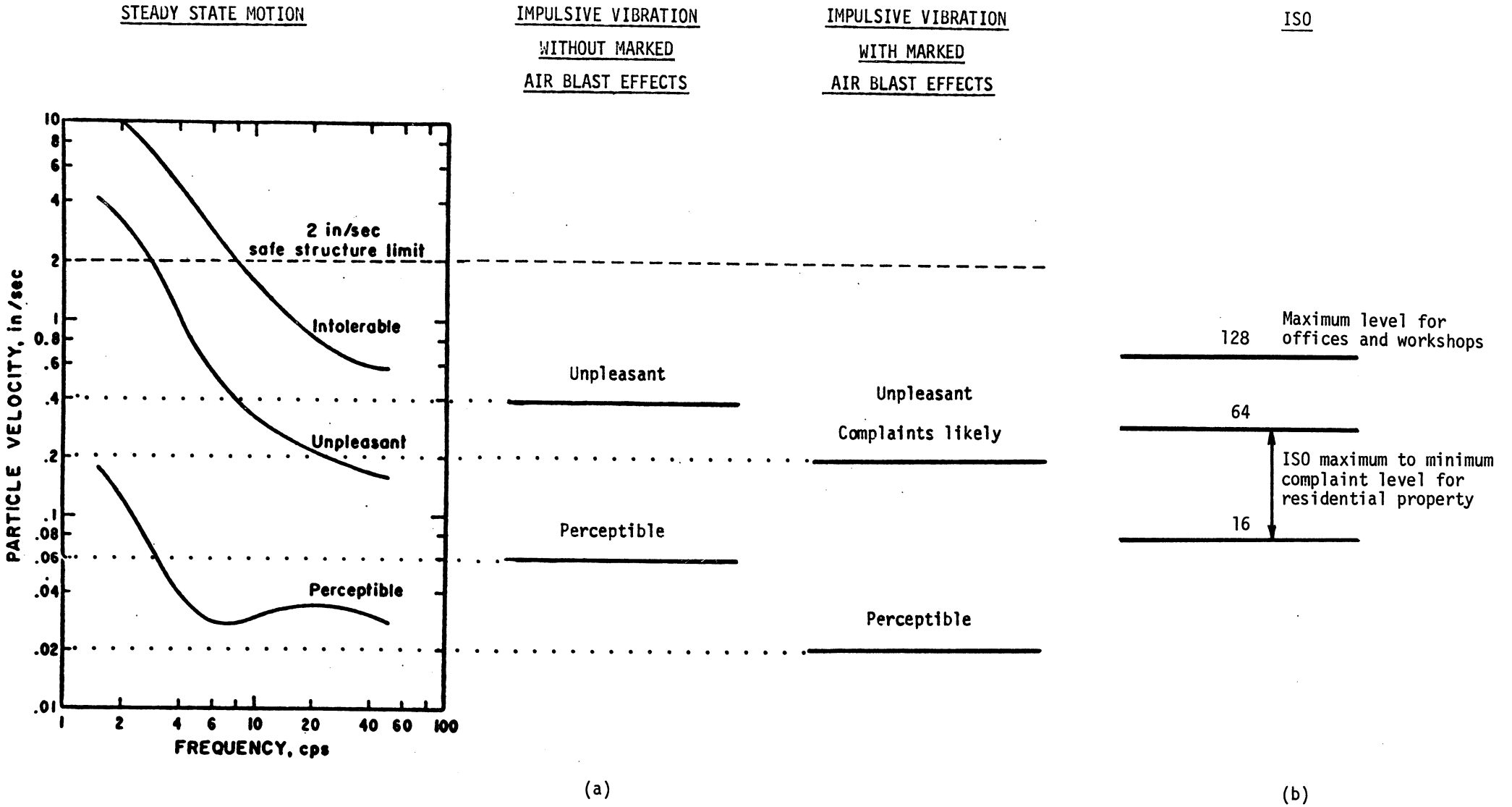


Fig.6. (a) Subjective response of human body to vibratory motion; (b) the levels corresponding to ISO weighting factors for offices and residential property

MR G.A. FOSTER (Vibra-Tech Engineers, Inc., Rockville, Maryland, USA): I am concerned that a level for minor damage from blasting as low as 5 mm/s is included in a document with the imposing title of an international standard. In the USA, where pre-blast inspections are commonplace, we know of no case of damage occurring after such an inspection at levels less than 50 mm/s. Many claims of damage have been made and settled at much lower values but in each case there was no prior record of the existing condition of the house. The imposition of the 5 mm/s level would in most cases prohibit blasting.

Our experience has shown that numerical values of the ground motion from blasting bear little or no relationship to the complaints received. Human response to blasting vibrations varies with a person's age, state of health, whether the person is sitting or standing and to a great degree on how the blasting operation is perceived. A short-duration operation providing some benefit to the person will be tolerated, but when the operation is continuous the same vibration effect can be effectively transformed into an intolerable one. The role of the accompanying air blast in producing complaints has been neglected in the ISO document. Fig.6(a) shows our experience that the presence of air blast effects greatly accentuates human response to blasting.

We strongly feel that the ISO standard as it relates to blasting vibrations is an academic folly which is not backed up by any known and accepted data. We strongly suggest that some input from other authorities such as the US Bureau of Mines and explosives users be considered before the standard is adopted.

DR ASHLEY: The proposed level for minor damage from blasting in the range 5-30 mm/s is part of another ISO working document being considered by the committee concerned with structural vibration. The standard discussed in my paper is concerned with the effect of vibration and shock on man in predicting the levels at which complaint is likely. Complaint levels are significantly lower than structural damage levels. I would agree with your comment that 5 mm/s is far too low for a structural damage criterion.

Figure 6(a) seems broadly in line with the ISO proposals on impulsive shock limits related to human response (Fig.6(b)). The level of 128 for offices and workshops is well in the range of being unpleasant, with complaint likely. The proposed ISO range of 16-64 is in the area of likely complaint. This level could perhaps be reviewed by the ISO committee to be slightly higher and to cover a range of 32-128, seeing as how it would apply to only three occurrences per day. As you rightly say, people will put up with higher levels of shock, provided they feel the construction work is for their benefit and will be only of a limited duration. I cannot but agree with you that any ISO recommendations for structural limits for buildings must take into account the work of such organizations as the US Bureau of Mines, and should not be put at an artificially low figure.

MR M.J. BALL (Nobels Explosives Co. Ltd, Newcastle-upon-Tyne): In the UK very few houses are built with basements or cellars and hence it is very difficult to locate vibration sensors at or near foundation level. Thus the vibration engineer has to place the sensor at the most convenient point, which may be on a concrete kitchen floor inside, or outside on, say, a concrete surround, or on a window ledge, and so we could well be measuring higher transfer factors anyway. We would concur with the wisdom of three-dimensional recordings plus time/frequency trace but would question the levels suggested at which damage may occur. It seems strange that only W Germany in DIN 4150 are proposing to adopt such low limits when this seems to be in conflict with other authorities such as the US Bureau of Mines, Australian National Standards Institute, AFTES in France etc., all of whom adopt significantly higher vibration levels for the caution zone than the DIN 4150.

Our own extensive experience in the UK suggests that somewhere in the region of 25 mm/s is perhaps over-cautious and there are many quarries and undertakings regularly producing peak particle velocities in excess of 25 mm/s at local habitations without causing damage. It can be stated that people will complain long before there is any chance of damage and this approach is followed to a certain extent in the UK.

On the question of the proposed international standards for blast-generated vibrations in buildings, we in the trade are somewhat concerned about the lack of contact and opportunity to participate in formulating such standards and we are perturbed that users and the industry in general have not been consulted. Perhaps it is a case of fringe users and academics imposing unacceptable standards on the industry and it is felt that industry should be given the opportunity to co-operate through such organizations as the Institute of Explosives Engineers, Quarry Managers Institute, British Quarry and Slag Federation and the Institute of Tunnelling Engineers.

DR ASHLEY: Mr Ball's comment on foundation fixing and possible amplification is a valid one. The whole difficulty of measurement and amplification has been dealt with in some depth in the paper by Dr Medearis mentioned in his contribution below, and I recommend Mr Ball obtains a copy. The ISO amendment discussed in my paper is concerned with response of humans to vibration, and only indirectly refers to possible structural damage. The more evidence which is available showing successful blasting with peak particle velocities greater than 25 mm/s, the easier it will be for a realistic standard to be adopted as far as structural damage to buildings is concerned.

DR SKIPP: It is unfortunately true that the representation of explosives engineers on the International Standards Organization working group dealing with vibrations and structures is weak. It is also evident from recent work² that the ground motion threshold for incipient

damage to low-rise buildings (at least for nuclear explosives) can be less than previously expected. The difference in frequency content between large distant explosions and nearby small precision blasting would contribute to the wide disparity of observation. It is probable that in terms of a single parameter such as particle velocity there is no true 'threshold'. A standard must then take into account an 'acceptable' risk that, even by complying with its requirements, there is a possibility of some damage. This damage may be small and repairable, but to an unprepared householder it can be 'unacceptable'. It is clear that the 'threshold' values quoted in recent drafts are by UK practice unnecessarily stringent for many applications of blasting in urban areas. It is hoped that good measurement and objective appraisal of damage, however slight, can substantiate the levels of 25 mm/s quoted by Mr Ball, at least for UK conditions.

DR SPLITTGERBER: The transfer factor (ground-building) will change if the vibration pick-ups are located not at or near the foundation but, for example, on a concrete kitchen floor or on a window ledge. In the German standard DIN 4150 the limiting values given for the caution zones are related to measuring points at the foundation.

Proposing and proving limiting values with reasonable arguments, for example, for the resultant velocity as a quantity and perhaps further parameters is in principle a statistical problem. If sufficient data are available, appropriate limiting values should be stated by quantifying the risk using adequate confidence coefficients. The values given in DIN 4150 do not seem strange because of the low levels. Comparing these limiting values, for example, with the values of the Australian standard CA23-1967 and the SAA explosives code, there is a fairly good agreement. The 'amplitude limits' given in section 10.7.4.1 of the Australian standard are related to ground vibrations, whereas the values in DIN 4150 are related to vibrations measured at the foundation. Supposing the mean value of the transfer factors $v(F-0)$ of the velocity amplitudes is in the range of 0.5, the limiting values of the Australian standard can be related to the foundation measurements. Taking this factor into account, vibration caused by blasting should not exceed the following limits according to the Australian standard:

$$v_R \leq 3.1 \text{ mm/s at } 5 \text{ Hz}$$

$$v_R \leq 6.2 \text{ mm/s at } 10 \text{ Hz}$$

$$v_R \leq 9.6 \text{ mm/s (one half of } 0.75 \text{ in/s) at } f \geq 15 \text{ Hz.}$$

In DIN 4150 limiting values of $v_R = 4-8$ mm/s are quoted for residential buildings, independent of frequency in the range from a few hertz up to 60 Hz.

DR K. MEDEARIS (Kenneth Medearis Associates, Fort Collins, USA): I believe the ISO recommendations should consider and incorporate the results of a recent treatise (by this contributor) on that subject. That treatise covers

research sponsored by 23 US and Canadian organizations, and is entitled 'The development of rational damage criteria for low-rise structures subjected to blasting vibrations'. A paper covering that work was recently presented at the 18th US Symposium on Rock Mechanics, Keystone, Colorado, USA. Briefly, the research results include the dynamic characteristics of 63 low-rise structures and some 200 blasting ground motion components, and a rational damage criterion for 1, 1.5 and 2 storey structures is presented. It is shown that neither peak ground velocity nor acceleration is as valid a damage predictor as structure spectral velocity response. It is intuitively obvious that a peak velocity criterion is not valid because it does not take account of the frequency characteristics of the ground motion or the structure being excited. Finally, the horizontal beam model shown by Dr Splittgerber in his explanation is not applicable because low-rise structure damage is almost always the result of lateral, not vertical, motions.

DR ASHLEY: Since receiving the above contribution I have been pleased to have the opportunity of reading a copy of Dr Medearis's paper, 'The development of a rational damage criterion for low-rise structures subjected to blasting vibrations', which was prepared for the National Crushed Stone Association. In that document Dr Medearis develops a technique in which limiting peak ground velocity is related to the number of storeys of the structure and the distance from the disturbing source. From that it would appear that for distances less than 100 ft to the source a peak ground velocity of 25 mm/s should be acceptable. This document must obviously be taken very seriously when the ISO document concerning damage to buildings by vibration is formulated. In the meantime the published ISO amendment is one of limits for occupants only, and makes only small reference to damage in Note 4 on Table 1.

MR M.T. TANTAWY (Association Française de Séismologie Expérimentale, Paris): I think that we have to take into consideration not only the ground waves but also the waves transmitted by the air.

Regarding the perception of man in buildings, it is necessary to consider (in the case of quarry blasting) the signal-to-noise ratio, where noise is the permanent vibration before and after blasting (from traffic etc.).

To study the effect on constructions we have to classify them. I am astonished that there is no mention of historical monuments and many other special structures (elevated water reservoirs etc.).

I think that to give any conclusion concerning the effect of vibrations a detailed interpretation has to be made, taking into consideration displacement, particle velocity, acceleration, frequency and time. Before interpretation, a study must be made of the origin of the vibrations, the nature and topography of the soil and the nature of the foundation, and the classification of the construction.

We have to take into consideration the indir-

ect effects of vibrations (compression of non-consolidated soils) especially for building in districts with great slope.

DR ASHLEY: Your comment on air-transmitted waves agrees with Dr Medearis in his report mentioned above. However, the criterion on damage is not a significant part of the ISO amendment as given in the paper. A further amendment relating to building damage is being prepared and obviously air blasting must be taken into account. The current amendment, however, is limited to the effects of vibration and shock limits on the occupants. In the majority of residential houses the vibration background is far below the perception level, and I do not think it plays any significant part in the perception of man to vibration under normal circumstances. When an ISO standard is proposed for acceptable limits for buildings as such, then we must take into account the special protection required for certain buildings, particularly historic monuments. Your last point amplifies the difficulty of the problem when we attempt to define the threshold limits of damage for buildings as opposed to their occupants.

DR P. SRINIVASULU (Structural Engineering Research Centre, Adayar, Madras, India): Paragraph 1 of section 2.5 in the appendix to the ISO standard 2631-1974 gives a vague meaning of the vibration quantity to be measured 'under different situations' - which are not clearly specified. If steady-state vibration is implied, the paragraph may as well be deleted as the matter is evident. Otherwise, the situations where different vibration quantities should be directly measured with appropriate transducers and the frequency limits within which they are applicable should be stated in the code for clear guidance to users.

In paragraph 3 of the same section, third octave filters and constant bandwidth filters are referred to, with no definite guideline suggested for the situations in which each type is recommended. This is a matter of detail concerning the type of instrument to be used and may be out of direct relevance to the text.

The last paragraph in section 2.4, which suggests that the weighting factor for an operating theatre in a hospital is unity because of the stated desire of the patients to be in touch with the 'outside world' seems rather unconvincing. The operating theatre is a special environment in which the vibration tolerance should be more stringent than even a residential environment. The weighting factor may be higher still for this.

Clarification is required as to when the combined Standard (Fig.4) is recommended to be used in preference to the assessment based on individual vertical or horizontal vibration data (Figs 2 and 3). Does the standard imply that either approach will lead to the same interpretation of the measured values?

DR ASHLEY: The proposed method of measurement using acceleration or velocity was left rather vague so that people who had existing equipment could continue to use it to meet the proposed

standard. The standard does suggest that in future acceleration and integrated acceleration to give velocity are preferable. As far as analysis by filters is concerned, the international standard dates back a considerable period of time when third octave was preferred. Third octave analysis is easier to understand with respect to the standard than narrow band. However, more recent work suggests that the overall weighted approach is more applicable than third octave analysis, but the international standard has yet to be updated to include this information. The document on building vibrations is intended as an amendment to the standard and must follow the same procedures as the standard until the basic document is reviewed. The reference to narrow fixed bandwidth analysis is to indicate that the modern type of real time analyser is applicable for identification of the troublesome frequencies.

The level recommended for a hospital operating theatre is half that recommended for residential property by day. The general level in hospitals should be the same as for residential properties.

Use of the combined Standard is covered by section 3.4. The applications of it are suggested as preliminary surveys and for conditions where dual use of the building, in terms of lying and standing, is probable.

MR C.P. LEWIS and MR R. BALL (Lanchester Polytechnic, Rugby): The Conference has shown that there is a need for sensitive acceleration, velocity and displacement measuring systems. In Paper 12 it is indicated that frequencies below 1 Hz are of significance in seismic measurements and that in some respects the old instruments have a better design than modern equipment. Dr Ashley in Paper 16 proposes that systems based on the use of an accelerometer followed by a double integrating process has advantages for building vibration investigations.

At Lanchester Polytechnic there has been continuous development of a lightweight portable signal processor which will operate at frequencies below 1 Hz with minimum phase distortion, and will provide acceleration, velocity and displacement signals. Particular attention has been paid to the simplicity of operation of the signal processor, the minimization of the power consumption and the weight. The sensitivity of the equipment is such that the following ranges are provided:

acceleration	0.001-0.1g
velocity	0.1-1000 mm/s
displacement	0.001-1000 mm

The system is so designed to remove the drift that occurs in some types of signal processing as is evident in Figs.8 and 10 of Paper 11.

Successful measurement of particle velocity and displacement has recently been made in buildings in a large engineering complex where a suitable position for expensive computer-controlled graphical equipment was required.

It is believed that the technique used in the signal processor is capable of further development if the observation of very low frequencies is of paramount importance.

DR ASHLEY: Since the Conference I have had the opportunity of viewing the equipment designed and developed by Messrs Lewis and Ball. The results I saw fully justified the technique, and I look forward to having full information on their proposed approach.

From the weight of the discussion, it would appear that there is considerable disquiet that the proposed ISO amendment relating to human response to vibration and shock in buildings could be used to limit ground velocities for reasons of structural damage. It is essential that the amendment makes it clear that it is concerned only with human response to vibration and not to structural limits. It is also important that when the ISO document is prepared on structural limits of vibration and shock in buildings it is

based upon a wide spectrum of evidence and is pitched at a level which allows normal types of building operation to proceed. In particular, the case of construction by blasting, which gives rise to high particle velocities at widely spaced intervals of time, must be given particular consideration.

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Closing address

D. B. O'Neill (J.H.A. Crockett and Associate, Carshalton)

When this Conference was first proposed I had intended it to be directed solely towards civil and structural engineers. The suggestion that earthquake instrumentation should be included worried me, lest the diet enjoyed by engineers should be indigestible to seismologists and vice versa. I do not think that I need have worried unduly for the papers have been consistently interesting and the discussions lively. Indeed, I feel sorry to have had to interrupt the discussion on the last session.

It is gratifying to see so many engineers taking an interest in vibration instrumentation. I hope this is because they are becoming more aware of their impact on the environment rather than because they are being forced to do so by the Control of Pollution Act.

Generally local authorities are not well versed in vibration control - although many now have noise problems fairly well in hand, and it is good to see representatives of some of the more enlightened authorities at the Conference.

I have little knowledge of seismology but I have been greatly interested in the problems discussed. I noted that discussion of earthquake instrumentation was really confined to Dr Willmore's explanation of instrumental development and Dr Long's mention of a foolproof tape recorder. Their instrumental techniques are now well established though still, no doubt, developing. Their research seems now to be into the field of interpretation and prediction; it appears to me, from listening to the papers and discussion, that one of the major seismological problems remaining to be solved is the establishment, for design purposes, of a suitable earthquake time history either of acceleration or of displacement. (There does not seem to be total agreement concerning the most suitable parameter among seismologists any more than among engineers.) Only when such a design earthquake or group of design earthquakes can be established for application to any given conditions can the powerful tool of model response, described by Dr Medearis, be properly applied to the design of structures and the prediction of behaviour of existing structures.

The papers to the engineers dealt largely with instrumental methods, field use and case histories. In the instrumental world the search continues for the ideal instrumental specification, although I feel that cost and the diversity of requirements will make success unlikely in the immediate future.

The question was posed as to whether the age of 'do it yourself' recording had arrived with the advent of hired instruments. I think we must appreciate the danger that exists in inexperienced use of instruments. The fact that one can hire high quality microphones and tape recorders does not ensure faithful 'high fidelity' recordings of music or bird songs, and any vibration recording programme must also be devised by experienced personnel if it is to yield accurate and reliable data. Even more importantly, the results must be interpreted by experienced engineers. This was well illustrated in several papers. It is only too easy for a recording to be useless, and perhaps even dangerously misleading, due to minor faults in operation of an instrument or by badly fixed or located transducers. However, there is no reason why any engineer, even if he starts by relying on a specialist, should not, with experience, become able to operate a range of instrumentation himself, especially long term monitoring instruments; but judging from the discussion on the relevance of standards and vibration limits, the interpretation of recordings (other than the obviously safe or the grossly dangerous) is still a matter for a person who can draw on considerable experience of previous incidents.

With regard to the vexed question of safe limits or standard recommendation - and I think this applies equally to earthquake engineers - there is no vibration limit for any building, under any predictable condition, below which it is safe from any damage and above which it is not. There is a huge grey area of no man's land between the positively safe and the positively unsafe. It is not possible to define vibration limits rigidly and yet there is an equal danger in loosely defined standards. Therein lies the dilemma.

A standard by its very nature will be applied indiscriminately to a multitude of vastly different conditions. We have only to recall the observations of Dr Morris who in 1950 published his calculation concerning brick walls and piers which could suffer damage if the horizontal displacement amplitude of their foundations greatly exceeded ± 0.008 in. Years later this displacement amplitude was being inserted into engineering specifications, independently of frequency, for any conceivable type of building, for both horizontal and vertical vibration, on the building foundations as well as on the soil. I even recall hearing an 'expert witness' in court quote this as the limiting safe amplitude for

vibration of a suspended concrete floor!

We should therefore be very careful to specify clearly the application of our standards and yet not to be so rigid that intelligent interpretation is inhibited. Dr Skipp suggests a 'danger ratio' to indicate the probability of a number of buildings in any given risk zone suffering damage from a specified vibration limit. This is a similar approach to my own practice of allotting what I call a 'degree of risk' to an individual building at hazard so that those finally responsible are guided in their acceptance or rejection of the risk involved.

The ISO standards, proposed to prevent annoyance to persons, seem to be basically sensible for long term intermittent disturbances, but perhaps some better provision could be made for

periodic disturbances with variable 'on' time in a similar manner to the Leq in noise control. In tunnel blasting operations, any standard should be a recommendation for a level to prevent unacceptable damage to average buildings, since it is impossible economically to restrict the vibration to a level ensuring human comfort. My own practice in such matters is to set a target within which the contractor is expected normally to operate, and a higher limit which must not be intentionally exceeded, its sole purpose being to cater for the occasional unexpected peak. The subject of standards has given rise to some lively, almost heated discussion, to which I have now been able to contribute. Dr Ashley has received your criticisms and will no doubt give them due consideration.