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12. Preliminary investigation of factors affecting rock vibration.

D.E. Leaman

As the agency controlling the use of explosives in Tasmania the Department of Mines often receives complaints related to damage, or supposed damage, resulting from the use of explosives. In recent years city growth has surrounded quarries and major public works have been required in built-up areas and thus there has been a consequent increase in complaints. Complaints are sometimes related to traffic vibration (*e.g.* Leaman, 1972). It should be noted however, that most complaints are related to air vibration rather than ground vibration.

In order to avoid damage, yet realising that the human body is itself very sensitive to small vibrations, an arbitrary limit on particle velocity has been imposed, this being a fraction of what has been accepted in Australia and overseas as causing damage. There has been considerable debate in the literature as to what the damage threshold is and how it should be defined. In some cases there has been a detailed analysis of the explosives, building damage and vibration characteristics during a construction programme. However, since there has been no direct correlation, or description, of rock type, rock quality, structural properties or seismic data it is never possible to simply or directly apply the information elsewhere. In the author's view the data recorded and considered in typical vibration engineering practice is incomplete since it lacks a time origin and full wave analysis. All results are empirical, commonly arbitrary and based on a neglect of geological considerations.

This arbitrary approach has often lead to unexplained and unexpected results.

A programme of test blasting is needed to establish vibration data for Tasmanian rocks in order to obtain predictable results. This report presents a summary of the results obtained in preliminary tests aimed at establishing guidelines for the investigation.

EQUIPMENT

GT2A seismograph: This instrument is normally used for shallow refraction surveys and is capable of providing records up to 1 second with up to 12 traces. Impact time and 10 ms timing lines are provided on the record. In the tests to be described no more than 5 channels were used so as to provide an uncluttered record of the full waveform.

Bison 1570B enhancement seismograph coupled with wide range geophone: The instrument is capable of displaying a detailed waveform over various time ranges (25-500 ms) as well as providing a time base which permits marking and identification of any wave character. The time origin is also provided. It is possible to examine the effects of coherent interference using the enhancement property of the instrument.

Motor driving an eccentric weight: This device was used to impart a range of vibration frequencies to the soil. It is capable of operating from 15-100 Hz. It was possible to pick the resonant frequency using the GT2A seismograph.

DEFINITIONS

Amplitude of an oscillatory motion, A, is the maximum displacement of the oscillating particle from its equilibrium position.

Similarly *velocity* (*v*), *acceleration* (*a*), *period* (*t*), *frequency* (*f*), apply to an oscillating particle. *A, v, a, f* are related as shown in a later section.

The term *frequency spectrum* is used to describe both the range of frequencies present and the emphasised frequencies.

The *fundamental frequency* is the lowest frequency indicated and in some cases may not have been directly observed but may be deduced from a study of harmonics.

Harmonic frequencies are integral multiples of the fundamental frequency.

Partial harmonics is a term used to describe rational multiples of the fundamental, not necessarily harmonics.

Longitudinal velocity is the velocity at which energy is transmitted through the medium in a longitudinal direction and is quite distinct from the particle velocity. Normally derived from first arrivals.

The term *attenuation* has been used:

(1) As the percentage decrease in amplitude over a given time.
(2) As the exponent in the complete wave equation.

Interference occurs whenever two or more waves cause disturbance in the same material at the same time. *Beats* may be produced when the frequencies of the interfering waves are similar and the *beat frequency* may then be listed. *Destructive interference* occurs when the wave phases are such as to cause amplitude decrease rather than increase.

Resonance occurs whenever the imparted disturbance has a frequency very close to the natural frequency of the medium. The *natural frequency* is that frequency which tends to dominate all others in random vibration. Resonance effects may result in a disastrous built up of displacement. It has also been listed as the '*sensitive*' *frequency* in the tables.

Envelope is a term used to describe the shape of the vibration as a whole, *i.e.*, the form of the outer limits of the disturbance and neglecting the detailed form.

TEST SERIES A: DETERMINATION OF NATURAL RESONANCE AND DISPERSION

Two distinct procedures were employed to determine the frequency characteristics of a range of rock materials.

(1) The record obtained from the Bison seismograph was examined in detail and the frequencies present listed. A weighting factor for dominant frequency could be derived and, or, the fundamental reduced. In addition a frequency-distance plot can be drawn.

(2) The motor was driven at different rates and the record of 4 or 5 geophones at different distances examined using a GT2A seismograph. When the resonant frequency for the material is approached all traces will show increases in amplitude. All materials were found to be very responsive to this process which was normally applied after the first procedure had been employed thereby restricting the frequency range of the tests. 'Sensitive' frequencies were determined in this way.

Results

Fill, Cornelian Bay, Hobart.

Vibrations examined at 7.5, 15, 22.5 m.
Frequency spectrum (approximate values): 15.4, 18.5, 20.8, 23.8, 27.8, 35.7, 41.7, 62.5 Hz.
Fundamental: 15.4 Hz (actual calculated value, 15.6 Hz).
Partials implied: 1:6/5:4/3:3/2:9/5:9/4:8/3:4.
Noted at 7.5 m: 1:6/5:4,
at 15 m: 1:6/5:8/3:4,
at 22.5 m: 9/5:4.
Longitudinal velocity: approximately 300 m/s.

Sand dune.

Vibration examined at 7.5 m.
Frequency spectrum (approx.): 45, 60, 100 Hz.
Attenuation in 500 ms: nil recorded.
Fundalmental implied: 15 Hz.
Longitudinal velocity: 350 m/s.

Coarse Tertiary sand, quarry Derby-Winnaleah Road.

Vibration examined at 7.5, 15, 25 m.
Frequency spectrum (approx.): 24, 30, 33, 37, 40, 50, 55, 67, 83, 100 Hz.
Fundamental implied: 12 Hz.
Partials implied: 2:5/2:11/4:3:10/3:4:14/3:11/2:7:25/3.
Especially noted at 7.5 m: 3:10/3:4:14/3:11/2:7:25/3,
at 15 m: 5/2:11/4:3:10/3:4:14/3:11/2:7,
at 25 m: 2:11/4:10/3.
Longitudinal velocity: approximately 500 m/s.
Amplitude: 25% maximum at 500 ms.

Basalt talus, Leam-Hillwood Road.

Vibration examined at 7.5, 22.5, 30 m.
Frequency spectrum (approx.): 25, 30, 33, 39, 48, 59, 77 Hz.
Attenuation at 7.5 m: 15% at 250 ms,
at 30 m: 10% at 300 ms.
Fundamental implied: 12 Hz.
Partials implied: 2:5/2:11/4:10/3:4:5:13/2.
Especially noted at 7.5 m: 5,
at 22.5 m: 11/4:10/3:5,
at 30 m: 2:5/2:11/4:10/3:4:5.
Longitudinal velocity: approximately 600 m/s.

Clay soil, clay; Glenorchy.

Vibration examined at 9 m.
Frequency spectrum (approx.): 25, 33, 42, 48, 60, 100 Hz.
Fundamental: 12 Hz.
Beat frequency: 4 Hz.
Partials implied: 2:11/4:7/2:4:5:25/3.
Longitudinal velocity: approximately 700 m/s.

Weathered Permian sandstone, Beaconsfield.

Vibration examined at 15 m.
Frequency spectrum: 42, 56, 100 Hz.
Fundamental implied: 14 Hz.
Partials implied: 3:4:7.
Longitudinal velocity: 800 m/s.
Attenuation to 50%: 190 m/s,
to 10%: 230 m/s.

Tertiary sediments, east Badger Head.

Vibration examined at 7.5, 15, 22.5 m.
Frequency spectrum: 25, 31, 37, 43, 50, 68, 100 Hz.
Fundamental implied: 25 Hz.
Ground roll frequency: approximately 30 Hz.
Especially noted at 7.5 m: 1:3/2:7/4:11/4:4,
at 15 m: 5/4:7/4:2:11/4,
at 22.5 m: 1:3/2:7/4:2:11/4.

Tertiary sediments, adjacent Batman Bridge Park.

Test series 1: On landslip.

Vibration examined at 4, 7.5, 15, 22.5, 32 m.
Frequency spectrum: 13, 15, 16.5, 18, 22, 25, 30, 39 Hz.
Fundamental implied: 6.5 Hz.
Partials implied: 2:7/3:5/2:11/4:7/2:4:9/2:6.
Especially noted at 4 m: 39 Hz,
at 7.5 m: 22, 30 Hz,
at 15 m: 16.5, 18 Hz,
at 22.5 m: 15, 18 Hz,
at 32 m: 18, 22 Hz.
Sensitive frequency: 20-25 Hz at 15 to 45 m.
Longitudinal velocity: 380 m/s

Test series 2: Adjacent to landslip.

Vibration examined at 7.5, 15, 22.5 m.
Frequency spectrum: 25, 30, 32, 37, 40, 62 Hz.
Especially noted at 7.5 m: 32, 40 Hz,
at 15 m: 30 Hz,
at 22.5 m: 25, 30, 32, 40 Hz.
Sensitive frequency: approximately 30 Hz.
Longitudinal velocity: 900 m/s.

Tertiary sediments, Windermere.

Vibration examined at 15, 45, 90, 135, 180 m.
Resonance tests show 40-44 Hz to be the natural frequency.
The information is best shown in Figure 17.
Longitudinal velocity: 1450-1500 m/s.

Tertiary sediments, St Helens (on landslip).

Vibration examined at 7.4, 15, 22.5, 30, 45 m.
Frequency spectrum: 25, 29, 32, 38, 45, 59, 70 Hz.
Especially noted at 7.5 m: 45, 59 Hz,
at 15 m: 38, 45 Hz,
at 22.5 m: 32 Hz,

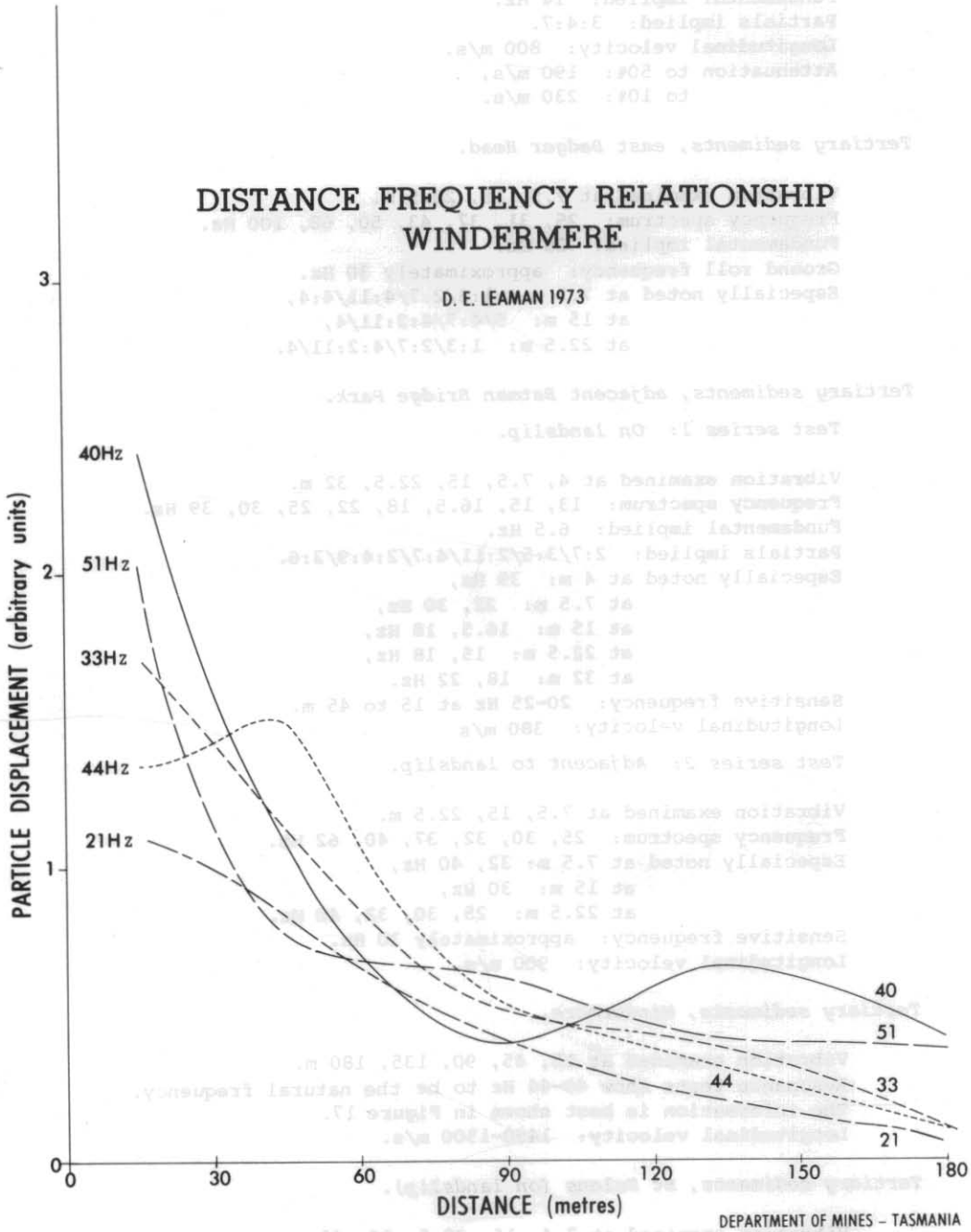

Figure 17.

5 cm

at 30 m: 25, 29 Hz,
at 45 m: 32, 59, 70 Hz.

The presence of a frequency of 70 Hz at a distance may be significant and suggests that it is a simple multiple of the fundamental (*e.g.* 7 Hz).

7/2:17/4:9/2:11/2:13/2:17/2:10.

Longitudinal velocity: 1250 m/s.

Weathered Triassic quartz sandstone, mudstone, Rhyndaston.

Vibration examined at 7.5, 15, 22.5 m.
Frequency spectrum: 23, 26, 29, 32, 36, 40, 50, 62.5 Hz.
Especially noted at 7.5 m: 26, 29 Hz,
at 15 m: 26, 32 Hz,
at 22.5 m: 26, 50, 62.5 Hz.

This material is variable in thickness and has failed in a series of landslips. Low frequencies are directly related to failed material whilst higher frequencies are related to more massive material. For the measurement at 22.5 m energy was applied away from a slip and the high frequencies were observed. The area is crossed by a railway line and a moving train on the slip area induced responses at 23, 26, and 32 Hz.

Mathinna Beds, West Mt William.

Vibration examined at 7.5, 15, 22.5 m E-W and at 15 m N-S.
Frequency spectrum: 110, 122, 140, 165, 185, 237, 292 Hz.
Fundamental implied: 36 Hz (indicated by long term sinusoidal background in record).
Partials implied: 3:7/2:4:9/2:5:13/2:16.
Especially noted at 7.5 m: 3:4:9/2:5:13/2:16,
at 15 m: 9/2:5:13/2:16,
at 22.5 m: 3:7/2:4:9/2.
Longitudinal velocity: 2200 m/s.
Amplitude attenuation: to 20% at 50 ms.

Dolerite, Domain, Hobart.

Vibration examined at 15 m.
Frequency spectrum: 31, 42, 50, 62, 83, 100, 125 Hz.
Fundamental implied: 31 Hz.
Partials implied: 1:4/3:8/5:2:8/3:16/5:4.
Longitudinal velocity (estimated): 2500 m/s.

Granite, St Helens.

Vibration examined at 7.5 m.
Frequencies along single granite slab: 172, >500 Hz.
Frequencies across two slabs: 116, 500 Hz.
Longitudinal velocity: >4000 m/s.
Attentuation equations:

Massive granite: $11.38t^{-0.0187}$; $f \sim 600$ Hz,
$6.28t^{-0.0133}$; $f \sim 172$ Hz.

Massive granite with a single joint: $7.94t^{-0.012}$; $f \sim 500$ Hz,
$8.17t^{-0.0153}$; $f \sim 500$ Hz,
$5.56t^{-0.0111}$; $f \sim 420$ Hz,
$5.49t^{-0.0083}$; $f \sim 116$ Hz,
$2.24t^{-0.005}$; $f \sim 116$ Hz.

Granite, Coles Bay.

Vibration examined at 5, 10, 16 m.
Frequency spectrum: 10, 20, 250, 500 Hz
(The cause of the low frequency vibration is unknown, but it may be related to shape of large joint blocks).
Longitudinal velocity: 4500-5500 m/s.

Basalt, Clarence Point, Kelso.

Vibration examined at 7.5, 15 m.
Frequency spectrum: 66, 83, 100, 166 Hz.
Especially noted at 7.5 m: 66, 100, 166 Hz,
at 15 m: 66, 83, 100 Hz.
Partials implied: 3/2:2:5/2:4.

(Simplified Fourier analysis shows the following weighting of energy at 15 m:

$A = 0.6$; $f = 66$; attenuation = 0.01
$A = 1$; $f = 83$; attenuation = 0.01
$A = 0.6$; $f = 100$; attenuation = 0.01

On this basis it is concluded that the fundamental is probably 41 or 42 Hz).

Longitudinal velocity: 5500 m/s.

DISCUSSION

The following general comments may be made:

(1) The rate of attenuation is directly related to peak frequency or fundamental frequency.
(2) The fundamental frequency is directly related to longitudinal velocity.
(3) Rock masses vibrate in a regular way. Any slight deviations between simple fractions of the fundamental appear to be related to errors in determination - usually due to the time scales selected.
(4) Although limited distances are involved dispersion is evident.

It will be noted that the table above contains mostly soft materials. Most tests of this type have been undertaken near landslips or material liable to slip in order to determine whether failure induces significant variations in properties. A rock such as dolerite, which has a wide range of properties, will probably provide a frequency signature for differing weathering states but this has not yet been established.

At present there is insufficient data to plot and statistically deduce the key relationships. The data do not include source-receiver distances of more than 50 m. Note that values quoted for attenuations are not wholly calibrated.

TEST SERIES B: THE EFFECT OF JOINTING

Massive and jointed granite at St Helens and Coles Bay was used in these tests. Granite was selected as it is more isotropic in bulk character than most other rock types and has simpler and more marked systems of jointing. The table below summarises the observations:

r = energy source to geophone distance (m)
f = dominant frequencies (Hz)
t = duration of vibration (ms). Subscript indicates particular frequencies where applicable.
δ = attenuation constants
v = longitudinal velocity (m/s)

r	f	t	δ	v	*State of rock*
5	20, >500			>5500	Massive slab
10	10, >500	100_{500}		>5500	Massive slab
16	10, >500	150_{500}		5500	Major joint at 11 m
16	10, 250, 500	50_{500}, 150_{250}		4500	Several major joints included.
7.5	172, >500		>0.018	>4000	Massive slab
7.5	116, 500		>0.012	>4000	Single joint
1	500	25			Jointed granite
3	500	28			Geophone alignment
7	500	18	*	~6000	parallel to major
9	330	16			joints. Many minor
11	450	10			but generally insignificant joints included.
5	500	22			Geophone-source alignment perpendicular to major joints.
10		7	*		
15	†	22			

†Detached arrivals which do not allow a reliable determination of frequency.
*Waveform terminates abruptly. No determination possible.

A very high frequency of vibration was common to all tests. As the wave velocity was also high it is concluded that all joints are closed at depth. The real effect of jointing is best seen in the first group of figures where there is a velocity reduction of 1000 m/s and in the second group where the vibration frequency is reduced. In the last two groups the presence of many joints had the effect of a coarse filter with abrupt termination of vibration after a short period.

Where large slabs are involved, as in the first group, a very low frequency form is present which may be related to the size of the block.

The above figures, suggest that the high frequency motion is directly related to massive, highly elastic material and is only sustained where the rock is uniformly massive. Allowing the given wave velocity this frequency could persist for up to 750 m. The low frequency, however, could be significant over 5000 m given an attenuation exponent of 0.1.

In all the above cases the displacement is very small, (less than 1-5% of that recorded in sand or soil with the same energy). In no case does the amplitude of the long period swell exceed the initial high frequency motion although it is more persistent in time.

TEST SERIES C: EFFECT OF OVERBURDEN

A consideration of the effects induced by overburden was made at Coles Bay where a 50 m section of jointed granite is overlain by 1-3 m of

WAVEFORM OVERBURDEN TESTS COLES BAY

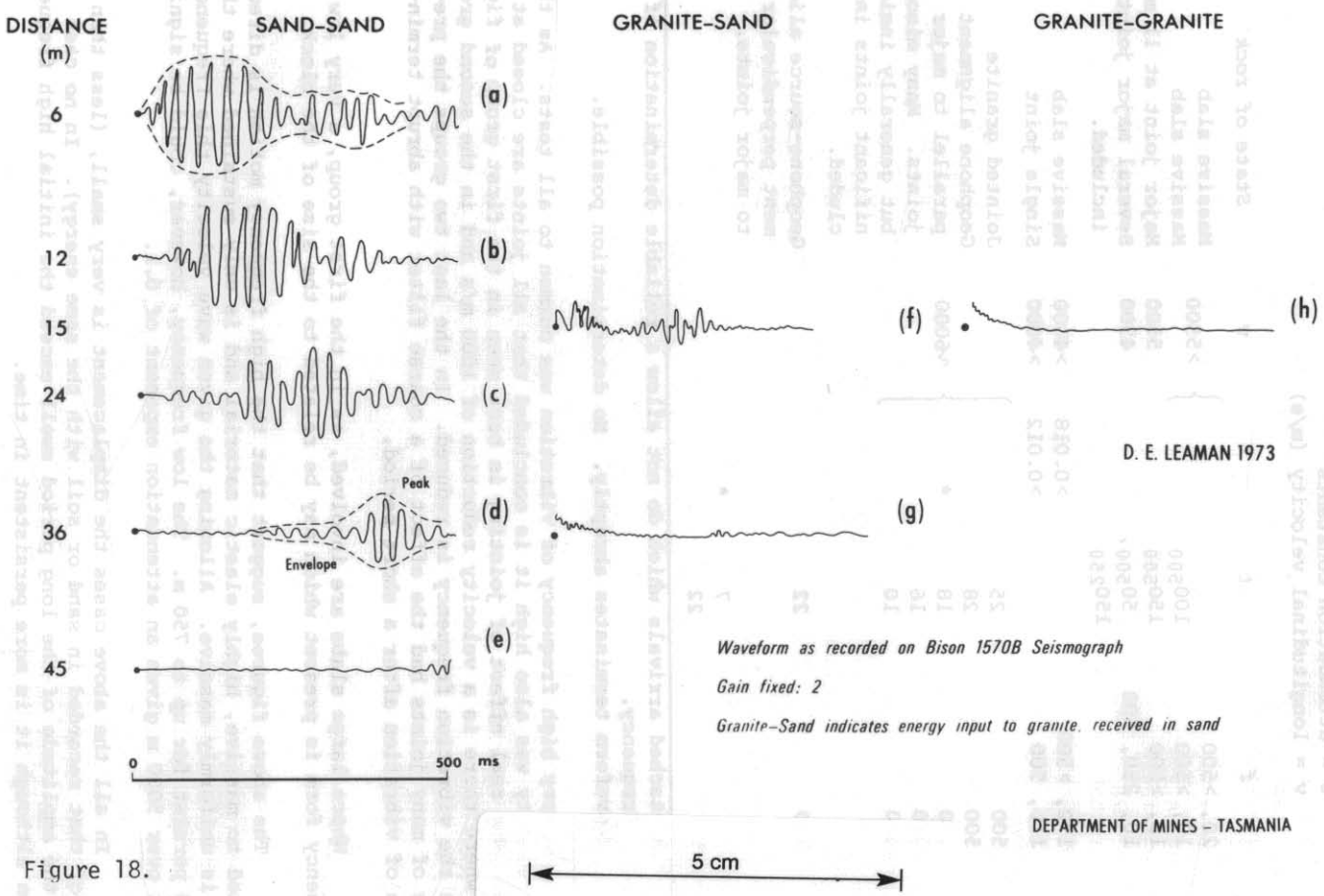

Figure 18.

beach sand. The longitudinal velocity in the granite was more than 6000 m/s while that of the wet sand was 1600 m/s. Refracted arrivals were received at distances of more than 5 m. As shown in Figure 18 the first arrivals arrive very quickly but are of very small amplitude whilst a high amplitude envelope follows at a very slow speed and contains frequencies of about 30 Hz. In this first series of tests both energy source and geophone were in sand. Higher frequencies are not evident in the records. The reduction of envelope amplitude with distance is also shown.

In a second series of tests the energy source was placed in granite and the geophone was left in sand. In this situation a granite decay curve and a diminished envelope were recorded. The amplitude of the envelope was about 5% of the sand-sand system envelope but its time position was fixed showing that the significant path is granite to sand with consequent energy loss followed by high amplitude propagation in the sand. It thus appears that low frequency overburdens markedly control the vibration amplitude at a receiver set in them even when the energy was directly applied to another medium.

A third test, where both energy source and geophone were on granite, produced a high frequency granite attenuation curve with no indication of a low frequency high amplitude wave. The tests represented by f, g, h in the figure reveal that rock transmission is fast and most energy arrives with the initial disturbance. This is not so in the overburden case (b, c, d, especially). It should be noted that records f, g, h represent coherent enhancement of energy from several hammer blows. Were this not done no useful analysis of the waveform would have been possible at the gain setting used since the displacement due to one blow was very small and thus the contrast between a-e and f-h is greater than appears in Figure 18.

The high amplitude envelope moves with a maximum velocity of 160 m/s, considering its initiation point only, and although the peak amplitude migrates in the envelope with time its speed also increases and approaches 160 m/s after 36 m. Peak amplitude refers to the point of maximum amplitude of the envelope.

The high amplitude waveforms described above and shown in Figure 18 could be Rayleigh waves. Love waves may also be present and directional tests will be necessary to examine these.

SUMMARY OF TESTS

Preliminary testing of rocks has demonstrated:

(1) Low frequency high amplitude transmission occurs in poorly consolidated (or weathered) materials.
(2) Rock jointing may play a significant role in filtering certain frequencies, controlling amplitudes or attenuating vibrations.
(3) The frequency of natural vibrations appears to be directly related to longitudinal velocity or bulk modulus.
(4) As noted in refraction theory there is considerable energy loss at boundaries between materials with varying acoustic properties.
(5) The wave group most likely to cause damage may move very slowly.

VIBRATION AND DAMAGE

As mentioned in the introduction there has been considerable debate as to which aspects of wave motion are damaging and how to specify them.

Various relationships between charge size, distance and amplitude have been produced but their validity has never been fully established. Such relationships can give accurate estimates, only for the particular conditions in which they were derived.

These problems, notwithstanding, it is possible to state that a high amplitude, low frequency motion will cause most damage. It should be noted that as the average kinetic energy density in a medium may be expressed as:

$$E = \tfrac{1}{4}\rho\omega^2 A^2 \left(E_{max} = \tfrac{1}{2}\rho\omega^2 A^2_{max}\right)$$

where ρ = density, ω = angular frequency, A = average amplitude

Thus in those situations where transmission occurs at high frequency, correspondingly smaller amplitudes are required for the same amount of damage for a given amount of energy. Note that low density materials with low natural resonance frequency will propagate at high amplitude or particle velocity. This latter fact can be seen from the following deriviation:

The simple harmonic wave equation is given by -

$$Y = A\sin(\omega t+E)$$

where y is displacement at any time t given a wave of maximum amplitude A, angular frequency ω and phase E. A simple harmonic motion is assumed here and experience shows this simplification to be a valid one.

$$\text{Differentiating; velocity} = A\omega\cos(\omega t+E) = v$$
$$\text{and acceleration} = A\omega^2\sin(\omega t+E) = a$$

Thus the energy equation may be written as -

$$E = \tfrac{1}{4}\rho v^2, \quad \text{where } v = A\omega$$
$$\text{or} \quad = \tfrac{1}{4}\rho A a, \quad a = A\omega^2$$
$$\text{Note } \omega = 2\pi f$$

These equations may be simplified to show directly the relationship between A, V, a and f.

$$i.e. \quad E = k.v^2$$
$$E = k.f^2.A^2$$
$$E = \frac{k.a^2}{f^2}$$

Thus for constant energy, it can be observed that increases in frequency require direct reductions in velocity or amplitude but increases in acceleration. Some values may be inserted as examples to demonstrate these properties of the energy relationship.

Frequency Hz	*Displacement* m	*Acceleration* m/s/s	*Velocity* m/s
20	$\sim 2.9 \times 10^{-4}$	~ 4.5	$\sim 3.65 \times 10^{-2}$
40	$\sim 1.45 \times 10^{-4}$	~ 9.0	$\sim 3.65 \times 10^{-2}$
100	$\sim 5.8 \times 10^{-5}$	~ 22.5	$\sim 3.65 \times 10^{-2}$

The above calculations presumed that E = 1 joule, ρ = 3000 kg/m^3. Note that all measures are inversely proportional to rock density.

Given good quality equipment it is possible to estimate the energy in any disturbance provided that it has been calibrated since frequency can be directly measured on the record produced. This estimate can be correlated with that input at the source as shown below.

It will be noted that those attempts to relate damage to velocity or displacement although including a frequency factor, must be of little real use since the duration of the effect is ignored. Obviously if a potentially damaging waveform persists for 2 or 20 wavelengths there will be variations in the damage noted. This being so the following damage criterion is proposed and future projects should examine its reliability, or whether there are significant advantages in its use over a simple velocity measure.

Presuming that damage is directly related to particle velocity and time of application

$$\text{Damage factor (DF)} \propto v.t$$

Since $v = A\omega = 2\pi Af$

then $\text{DF} = 2\pi Aft$

where f in Hz, t in seconds

A further possible criterion may well include some relationship of energy and frequency.

In summary, greatest damage is likely to buildings on unconsolidated or soft materials irrespective of the source of vibration. This follows directly from the observations of tests A and C. Soft materials propagate a high amplitude low frequency wave which persists for a longer time at a potentially damaging level, than corresponding vibrations in hard rocks.

EFFECT OF ROCK BOUNDARIES

The efficiency of energy transfer at rock boundaries was discussed briefly under test series C.

The ratio of transmitted to incident energy at a boundary is given by

$$\frac{I_t}{I_i} = \frac{4R_1R_2}{(R_1\ R_2)^2} \quad \text{where } R = \rho v \text{ (Pain, 1970, p. 114)}$$

(ρ = density, v = longitudinal velocity)

The following table gives the percentage of energy transmitted for a number of Tasmanian rock boundaries. The figures quoted are typical but will of course vary in particular situations. They should be regarded as a guide only.

Tertiary basalt/Tertiary clay

R (basalt) = 3000 x 7000 (very massive)
R (clay) = 2000 x 1800
I_t/I_i ∿ 45%

Tertiary sediment/water

R (sediment) = 2000 x 1800
R (water) = 1000 x 1500
I_t/I_i ∿ 86%

Jurassic dolerite/Triassic sandstone

R (dolerite) = 2900 x 7000 (very massive)
R (sandstone) = 2400 x 4000
I_t/I_i ∿ 93%

If dolerite velocity 5000 m/s
I_t/I_i ∿ 97%

Rock/fill

R (rock) = 2900 x 7000 (very massive)
R (fill) = 1500 x 700
I_t/I_i ∿ 20-25%

This latter figure, derived for materials similar to those at Coles Bay - test C, shows why there is such a major reduction in envelope size. However, in confined situations or where damage is possible great care would still need to be taken with charge sizes to ensure that low density, low velocity media nearby were not unduly affected. Although only about 20% of the energy incident at an interface of this type (a fairly extreme case) passes across, its wave character changes as described in the previous section, to a high amplitude low frequency form. Thus amplitude accentuation is inevitable, and consequently damage, unless the total energy level is low.

The calculation below demonstrates these properties:

Consider the effect of 45 kg charges at 300 and 600 m. Using the approximate relationship $v = H(\frac{d}{W^{\frac{1}{2}}})^{-\beta}$ (Duvall and Devine, 1968, p. 406) where v is peak particle velocity, H and β are constants, d is shot-observation distance and W is charge weight. It is possible to estimate the violence of vibrations emanating from a given charge. High energy explosives are considered here.

if d = 300 m, W = 45 kg, $v = 7.5 \times 10^{-4}$ m/s and
if d = 600 m $v = 2.5 \times 10^{-4}$ m/s

If the rock is good quality basalt or dolerite say, ρ = 3000 kg/m^3 then the energy involved at d = 300 m is 4.2×10^{-4}J and at d = 600 m, 1.4×10^{-4}J.

Displacements are 1.2×10^{-6} and 0.4×10^{-6} respectively. The energy calculations assume a vibration frequency of 100 Hz. If there is no variation in rock type the above figures would hold. However, suppose there is a rock boundary at 300 m such that only 50% of the energy is transferred (stiff clay).

i.e. 2.1×10^{-4}J is transmitted

If the frequency of vibration changes to 30 Hz, this energy is capable of producing a particle velocity of 5.3×10^{-4} m/s but an amplitude of 2.8×10^{-6} m which is more than double that present in massive rock at the same distance even though there had been a significant reduction in the energy involved. Note that these figures are averages only since the peak energy equation has not been used. Peak values could be four times as great.

The figures used in the above presentation demonstrate the effects to be expected. The validity of the attenuation relationship in Tasmanian rocks needs to be checked but may be used, as here, for estimation purposes. (In Imperial units v is in inches/sec, H = 85, d is in feet, W is in lb and β = 1.7).

IMPLICATIONS FOR FURTHER WORK AND DAMAGE ASSESSMENT

Effect of vibration on poorly founded buildings

The results of test series C have shown that unless a foundation is set in rock it will be subject to greater disturbance irrespective of the location of the energy source and the presence of discontinuities between source and foundation. Building regulations should insist on rock founding where this is possible at reasonable depths (>2 m) which is rarely done in practice. In those cases where damage claims are made it is essential to

place the detecting equipment in the same material and in positions or depths equivalent to the founding or failing material. Rock-rock tests must be undertaken with geophones at massive outcrops to be meaningful since rock-soil tests will reveal different properties.

Where the source of vibration is in the receiver medium, as is normally the case with traffic vibrations the situation may be very serious since disturbance durations of more than 1 second at 30 Hz and high amplitude may be common.

As a corollary to these comments it will be noted that some restrictions on haphazard development of services within an area may be needed. Excavation for a pipe or cable on a vacant allotment may cause damage on neighbouring properties. The solution to most such problems would appear to be:

(1) Avoid landfill where possible. Too many councils and developers prefer to build on fill rather than excavate foundations. This includes natural fills. Settlement either with or apart from vibration will also be a problem.

(2) Require developers to complete development so that minimal earthworks or excavations are required at a later date.

(3) Inform contractors that they may be liable for damage caused and educate them in reference to use of explosives, heavy equipment and recognition of problems.

Effect of vibration on well-founded buildings

Unless the source of the vibration is high in energy or very close, little damage is likely due to high frequency of vibration and low amplitude.

The use of explosives fired in series

It is standard practice to fire a series of delayed charges rather than one large charge. This has the direct advantage of reducing the impulse into the medium and hopefully provides for destructive interference, or cancellation of vibrations.

Intervals between detonators of the L series short delays, commonly used in Tasmania are 23, 32, 25, 25, 25, 25, 25, 24, 23, 23, 30, 30, 30, 30, 30, 30, 35. The figures quoted are delays in milliseconds. It will be noted that materials with resonant frequencies of 12-12.5, 15, 24-25, 30 millisecond period or 87, 67, 40, 32, Hz or multiples thereof will be strongly influenced by this type of firing.

In addition consider the potential constructive interference over a time period of 100 ms. Consider record (d) in Figure 18 where the high amplitude disturbance persists over this time range with frequency of about 30 Hz. A fourfold increase in amplitude is possible and the total duration of the disturbance would be considerably extended. Some destructive interference will occur but beating will be set up at high amplitude. In the author's view delay firings should be extended as much as possible but with consideration given to distance from charge, frequency, duration of vibration at damaging levels and length of wave train. As shown in the figure the envelope diminishes in magnitude and disperses with distance such that high amplitudes are maintained for short periods. If this period is less than the delay time no constructive interference will occur unless the firing frequency happens to be the resonant frequency of the rock mass.

DETAILED PROJECTS REQUIRED

Tests need to be undertaken in a range of geological environments and those suggested for examination are:

(1) Basalt, dolerite, granite, Permian siltstone - fresh, jointed and weathered.
(2) Limestone, as at Glenorchy, Ida Bay and Railton.
(3) Sandstone/mudstone of the Triassic succession.
(4) Slate, quartzite - folded rock types.
(5) Tertiary sediments and fill.
(6) Rock boundaries - dolerite/clay or fill and dolerite/sandstone.
(7) Faults.

Tests of vibrations in rock in various conditions; including soils are needed. Only broad classes are listed since longitudinal velocities, elastic moduli, and densities overlap and a broad range of results will be provided rather than possibly meaningless minor differences which can be assessed in special projects and will probably be given by surveys in dolerite areas.

The tests should determine:

(1) The effect of charge size on displacement* at various distances up to one kilometre.
(2) The effect of standard delays on displacement* at distances up to one kilometre.
(3) The effect of irregular delays.
(4) The natural frequencies of the rock mass.
(5) The attenuation factors.
(6) The effect of changes in weathering and jointing on displacement*.
(7) The effect of tests (1), (2) and (3) on rock masses comprising a wide variety of materials with special regard to energy transmission, channelling and resultant surface waveforms in both horizontal (Love) and vertical (Rayleigh) modes.
(8) The compressive and shear velocities for the medium, including Poisson's ratio.
(9) The density of the medium.
(10) The structures present: predominant jointing, dip of bedding, thickness of beds, schistosity, cleavage, faults.
(11) The effect of charge depth or charge concentration on the efficiency of breaking and the vibrations produced.
(12) The range of influence of traffic vibrations.

*The term displacement has been used above; velocity and acceleration can be derived from it.

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