Mountings for Measurement of Ground Vibrations

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SUMMARY Studies have shown that mountings which support vibration transducers for free field vibration measurement may interact with the ground in such a way as to reduce the accuracy of vibration measurement particularly for high frequency vibrations. These theoretical studies form the basis for assessment of the accuracy of the vibration measurements in the field using different mountings. Geophysical surveys have been carried out at a field site to establish the ground geometry and the stiffness characteristics of the ground. Comparisons were made between the observed vibration amplitudes measured on different mountings placed on or just below the surface of the ground. The mountings used were either plates (surface mounted) or rods (varying depth of embedment), an accelerometer being attached to the upper surface of the mounting in each case. The source of vibration used was an electromagnetic vibrator which generated sinusoidal steady state vibrations. Study of the experimental data shows an approximate measure of agreement with theoretical predictions for some series of measurements, but for other measurements there was relatively little agreement for reasons that are not understood at this stage.

1. INTRODUCTION

With respect to the measurement of vibration amplitudes at the ground surface, much attention has centered on the transducers themselves and their characteristics (eg. Bradley and Eller (1961), Richart et al (1970) and Hanna (1985)). Relatively less attention has been given to the mounting of transducers. Brown (1971), for example, describes measurements of ground vibrations caused by construction equipment and by blasting operations. The transducers were mounted on a block of aluminium but no further details were provided. More recently Grant (1983) described an investigation in which he concluded that the measured ground motion can be considerably influenced by the performance of the mounting. He found that mounting shape, size, material type and method of installation all played prominent roles.

Regarding the measurement of ground vibrations from blasting operations, Dowding (1985) has mentioned that the type of mounting is least critical when the maximum particle accelerations are less than 0.3g. For greater accelerations he suggests that the mounting should be partially or completely buried if the ground surface consists of soil. These recommendations are quite inadequate.

Regarding earthquake vibrations, Crouse et al (1984) have commented on the desirability of satisfying two criteria:

(a) the base dimensions of the mounting are much smaller than the wavelengths of the seismic waves and

(b) the natural frequencies of the mounting are much greater than the seismic wave frequencies.

While these criteria are necessary for the accurate measurement of ground vibrations, they must be quantified to be useful in practice.

A theoretical examination into the performance of mountings for measurement of free field vertical and horizontal vibrations has been carried out by Moore (1986, 1988). This work showed how the magnitude of the error in the measurement of vibration amplitude depends upon the vibration frequency, the mounting geometry, the ground rigidity and the natural frequency of the mounting.

2. TRANSMISSIBILITY

The precision with which the vibration transducer correctly measures the ground vibration amplitude may be indicated by means of the displacement transmissibility (T_D). For a vertical sinusoidal ground vibration of amplitude Z_0, the displacement transmissibility is given by

$$T_D = \frac{A_Z}{Z_0} = \frac{[1 + (2D\,\omega/\omega_z)^2]^{1/2}}{[(1 - (\omega/\omega_z)^2)^2 + (2D\,\omega/\omega_z)^2]^{1/2}} \qquad (1)$$

where ω = frequency of ground vibration

ω_z = vertical natural frequency of the mounting (+ transducer) on the ground surface

$= (k_z/m)^{1/2}$

k_z = vertical stiffness of mounting on the ground

m = total mass of unit (mounting + transducer)

D = damping ratio

A_z = amplitude of vibration as measured by the transducer.

The damping ratio for many transducers is either in the vicinity of zero or around 0.7. The types of transducers mostly used by the authors are Brüel & Kjaer piezoelectric accelerometers. As stated by Serridge and Licht (1986) the damping ratios for these instruments are very low. In the following discussion the damping ratio will be taken as zero.

From equation (1) it is clear that the transducer will provide increasingly accurate measures of the amplitude of ground motion as the displacement transmissibility more closely approaches unity. As illustrated in Fig. 1, this is best achieved at low values of the frequency ratio. For example Fig. 1 shows that for zero damping and provided the frequency of ground motion is no greater than 30% of the natural frequency (f_n) the maximum error in the measurement of ground motion amplitude is 10%. Fig. 1 also shows that the errors in amplitude measurement may become quite large when the frequency of ground motion is greater than 50% of the natural frequency of the mounting unless considerable damping is present in the system.

3. INSTRUMENTATION AND EQUIPMENT

In order to determine experimentally the magnitudes of errors in free field vibration amplitude measurements at different frequencies of ground motion, a program of field testing was commenced. This involved using vertically mounted transducers and various plate and rod mountings covering a range of sizes. The plate mountings were made of timber, aluminium or steel and varied in diameter from 100mm to 400mm and in mass from 140g to 126kg. The rods were made of steel and varied from 10mm to 80mm in diameter and from 50mm to 200mm in length. The transducer used was a Brüel & Kjaer piezoelectric accelerometer type 4370. This was used in conjunction with a Brüel & Kjaer Charge Amplifier type 2635 which produces an output voltage proportional to the charge coming from the accelerometer.

The source of vibrations was provided by a Ling dynamic System Model 409 electromagnetic shaker. This shaker has an operating frequency range from 5Hz to 9kHz, and a maximum thrust of 196N. The shaker was attached to a steel footing placed on the ground surface. A transducer was attached to this footing to monitor the vibrations transmitted into the ground. The mass-spring resonance within the shaker occurred at 30Hz so this frequency was avoided in field testing. For most of the field testing the displacement amplitude of the shaker footing was kept at 2μm.

The signal generating system for the shaker was a Hewlett Packard Model 2000 wide range oscillator. For the field testing all of the electrical equipment was run off a portable petrol driven generator.

After passing through the charge amplifier, the signal generated by the transducer was fed into a Hewlett Packard (Model HP 3566OA) dynamic signal analyser for provision of the final output.

4. FIELD TESTING

Testing was carried out at Lyndhurst near Melbourne, the site consisting of a deposit of siliceous dune sand of fine to medium grain size. The dynamic moduli at the testing site were evaluated by means of a number of seismic refraction surveys.

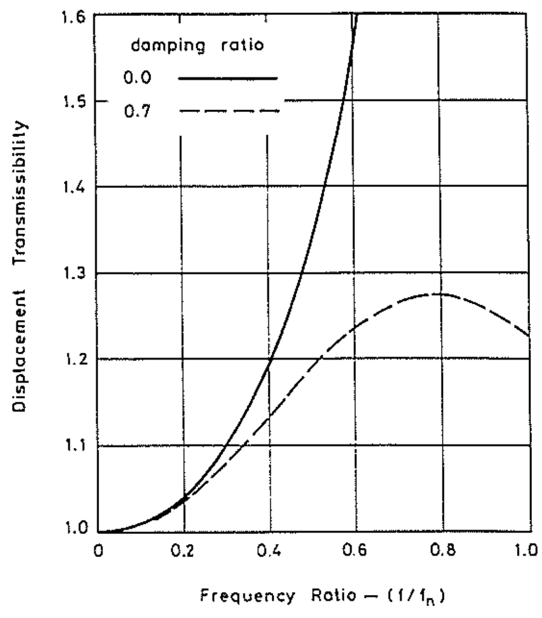

Fig. 1 Effect of Damping on Displacement Transmissibility

The geophones were placed collinearly in the ground and observations of first arrival times were made with forward and reverse shots. The results of two tests in the same general area with geophones spread over a distance of 45m are shown in Figs. 2 and 3. The results indicated that the P wave velocities varied slightly from test to test and that there was a small increase in velocity with depth. Overall it was concluded that there existed a surface layer of sand at least 5m in thickness with a shear modulus that was within the range of 27MPa to 33MPa. In calculating the shear modulus the Poisson's Ratio was assumed to be 0.3 and the soil density was measured at 1.9t/m^3.

Vibration amplitude measurements were carried out with the different mountings over a frequency range of 40 to 260 hertz. In most cases the mountings were located 1m from the shaker. Results for the timber mountings are shown in Fig. 4. No definite trends are apparent from this data. Since the calculated natural frequencies for these mountings (see Table 1) are relatively high the plotted data would appear to indicate the typical scatter of results to be expected at low frequency ratios with the ground motion being generally within the range of 5 to 10 x 10^{-8}m.

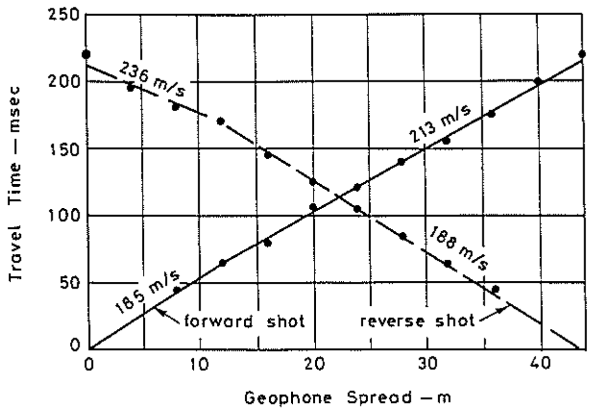

Fig. 2 First Spread Seismic Refraction - Lyndhurst Site

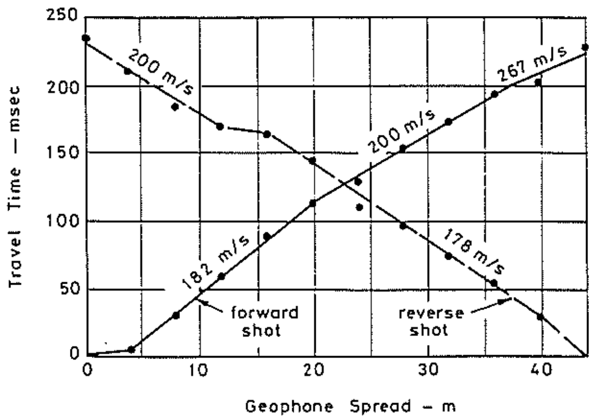

Fig. 3 Second spread Seismic Refraction - Lyndhurst Site

TABLE 1

Natural Frequencies for Timber Mountings

Diameter (mm)	Mass (kg)	Natural Frequency (hertz)	
		G = 27MPa	G = 33MPa
100	0.14	1180	1310
200	0.48	900	1000
400	1.7	670	740

Fig. 5 shows results of vibration measurements taken with aluminium mountings. At low frequencies the amplitudes are of a similar magnitude to those obtained with the timber mountings. At the high frequency end of the observation range there appears to be a noticeable difference between the amplitudes measured with different size mountings. The larger mountings generate the larger observed amplitudes and, as shown in Table 2, this is consistent with the calculated decreases in natural frequency.

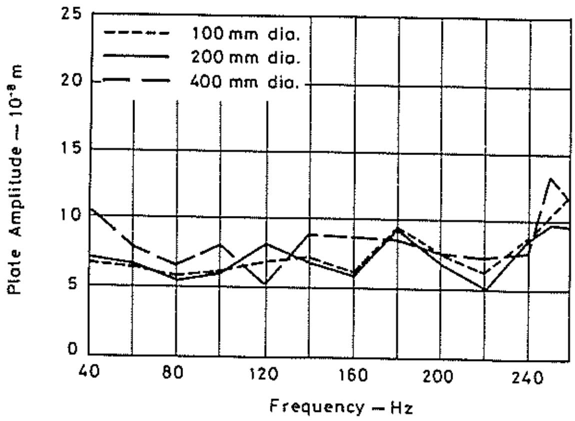

Fig. 4 Vibration Measurements with Timber Mountings

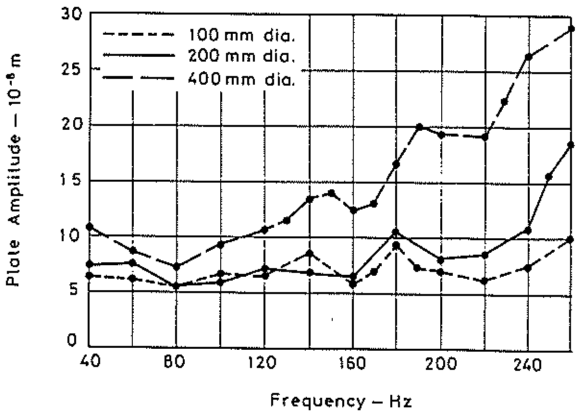

Fig. 5 Vibration Measurements with Aluminium Mountings

TABLE 2

Natural Frequencies for Aluminium Mountings

Diameter (mm)	Mass (kg)	Natural Frequency (hertz)	
		G = 27MPa	G = 33MPa
100	0.50	630	690
200	2.56	390	430
400	10.00	280	310

Figs. 6 and 7 show results of amplitude observations with mountings of different diameters and different total mass. With these observations actual peaks occur with the measured amplitudes. Based on the earlier discussion in this paper and on Fig. 1 those peaks would be expected to occur at or slightly below the natural frequency. As may be seen from the calculated natural frequencies in Table 3, such a level of agreement is only approximate.

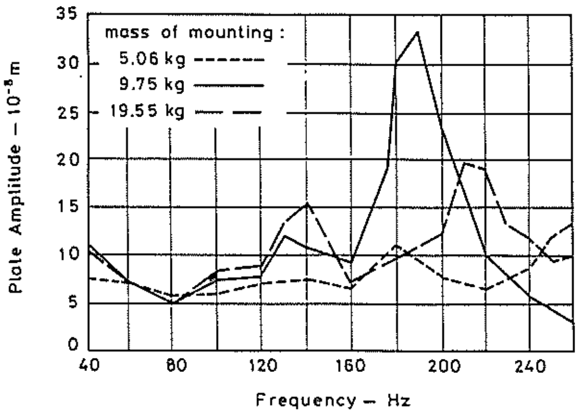

Fig. 6 Vibration Measurements with Steel Mountings - 200mm dia.

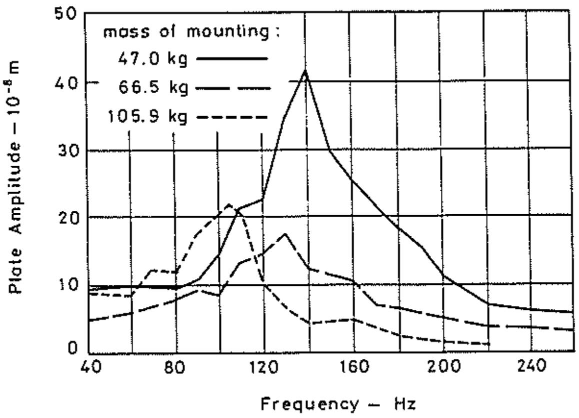

Fig. 7 Vibration Measurements with Steel Mountings - 400mm dia.

TABLE 3

Natural Frequencies for Steel Mountings

Diameter (mm)	Mass (kg)	Natural Frequency (hertz)	
		G = 27MPa	G = 33MPa
200	5.06	280	310
200	9.75	200	220
200	19.55	140	160
400	47.0	130	140
400	66.5	110	120
400	105.9	90	100

TABLE 4

Natural Frequencies for 10mm Dia. Rod Mountings

Length (mm)	Mass (g)	Natural Frequency (hertz)
50	25	2100
100	52	2000
200	108	1900

Fig. 8 shows the amplitude results obtained with steel rod mountings. At the high frequency end of the measuring range there appears to be a trend towards increased measured amplitudes as the rod length decreases. From Table 4 it is seen that the natural frequency increases as the rod length decreases. Additionally the natural frequencies are quite high in comparison with the frequencies used for the observations. It is considered that the measured amplitudes should provide a reasonable estimate of the ground motion and the reason for the apparent trend mentioned above is not known.

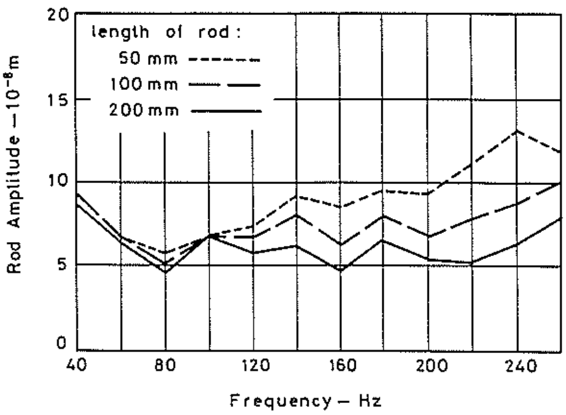

Fig. 8 Vibration Measurements with Steel Rods - 10mm dia.

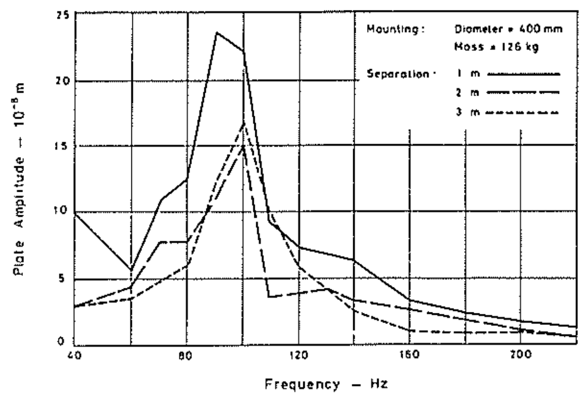

Fig. 9 Effect of Separation on Vibration Measurements

The effect of separation between the measurement point and the source of vibrations is illustrated in Fig. 9. The calculated natural frequency for this mounting is between 80 and 90 hertz so the observed peaks in the amplitude plots occur at slightly higher frequencies than would be predicted. This may be caused by increased stiffness of the ground resulting from the high confining pressure arising from this heavily loaded mounting. The expected decrease in observed vibration amplitude with increasing separation is only partially supported by these observations.

Fig. 10 shows comparisons between calculated and observed amplitude ratios for one particular mounting. The observed amplitude ratio is the ratio between the observed amplitude of the plate mounting and the observed average amplitude of the rod mountings, the latter being assumed to provide a reasonable estimate of the ground motion. The calculated amplitude ratios are based on the two estimates of natural frequency the curves

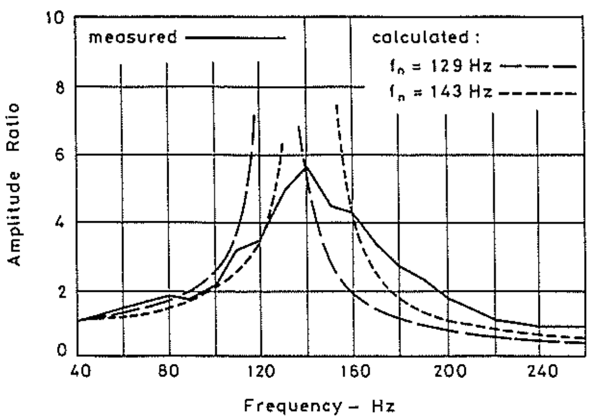

Fig. 10 Calculated and Observed Amplitude Ratios for 400mm dia. 47kg Mounting.

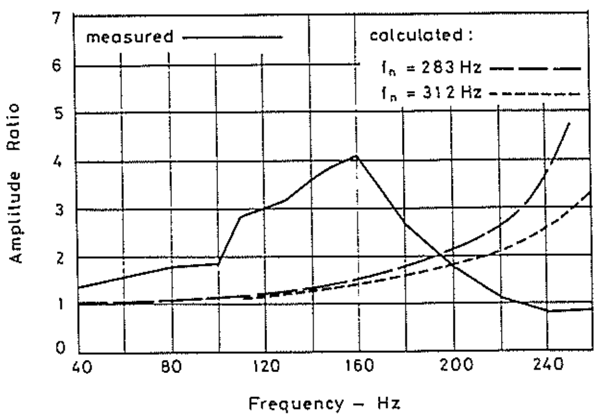

Fig. 11 Calculated and Observed Amplitude Ratios for 400mm dia. 9.8kg Mounting

plotted corresponding to zero damping. If allowance is made for damping which is clearly present in the observations then approximate agreement between calculated and observed amplitude ratios is evident. For some observations however this is not the case as illustrated in Fig. 11. The observed peak in the amplitude ratio in this case is significantly lower than the calculated peak for reasons which have yet to be understood.

5. CONCLUSIONS

For the majority of the vibration amplitudes observed at a field site, there is approximate agreement with theoretical predictions. The errors in vibration amplitude measurement tended to increase as the natural frequency for the mounting used, more closely approached the ground vibration frequency. In spite of the observed scatter in results the vibrations observed with the rod mountings appeared to provide the best overall estimate of the vibration levels in the ground.

6. REFERENCES

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