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# Experimental study of vibrations in underground structures

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Vibrations produced on the ground surface by engineering construction processes can damage underground structures. At present there is little knowledge of the level of surface vibrations that could cause such damage. The relevant British Standards, BS 5228 and BS 7385, have little relevance to underground structures. This paper presents experimental investigations on small model tunnels that were instrumented with miniature accelerometers. Impulsive and vibratory loadings were produced on the soil surface by a drop hammer mechanism and an electric eccentricmass motor respectively to simulate dynamic loading from construction activity. It was found that tunnels with different lining materials absorb different amounts of vibration energy. Power spectrum analysis of the acceleration signals showed that the vibrations are transferred into a brass model tunnel at lower frequencies than for a plastic model tunnel. A relationship has been proposed for the ratio of energy transferred and the ratio of impedance mismatch between soil and tunnel lining. Similar experimental studies can be carried out to understand the energy transfer from ground into underground tunnels with various linings (precast concrete lining, shotcrete or steel).

#### I. INTRODUCTION

Engineering construction processes such as piling, blasting, dynamic compaction and demolition produce ground-borne vibrations to varying degrees. These vibrations are transmitted through the ground as different types of stress wave. When these waves encounter an obstacle such as an underground structure, part of the wave energy is reflected and the rest is transmitted into the structure. The energy transmitted into the structure will increase the stress levels in the lining of the underground structure. These stress increases are usually small compared with the static stresses already present in the structure, but as these induced stresses are cyclic in their nature they could lead to fatigue cracks and produce significant damage in the long term. Thus it is important to fully understand the propagation of waves through the soil and what proportion of the soil vibrations is transmitted into the underground structure.

Nowadays, with the increased demand for land in major conurbations, construction activities increasingly tend to take place near the existing underground structures such as tunnels and buried services. At present there is little knowledge on the level of surface vibrations that could cause damage to such structures. There are many empirical predictors<sup>1-3</sup> for the peak particle velocity (ppv) in the ground away from a vibrating source, but these cannot be used to predict the ppv near ground inclusions such as tunnels. In order to use the predictors effectively near underground structures, we need to fully understand the transmission of vibration into such structures from the ground.

Investigation of the interaction between the soil and an underground structure under ground-borne vibration must be carried out in a geotechnical centrifuge, where representative stresses and strains are re-created in the model. This paper presents preliminary findings based on 1g experiments on small-scale models. Even though these tests were carried out at low stresses, useful information on the interaction aspects of underground structures was obtained.

# 2. APPARATUS AND EXPERIMENTAL TECHNIQUES

Wave propagation was studied using impulse and vibrating surface loads on dry sand placed in an 850 mm tub. The impulse load was generated by means of a drop hammer mechanism, and the vibrating load was generated by an electric eccentric-mass motor. Miniature accelerometers, buried at several locations, were used to measure the vibrations in the sand. DASYLab (Data Acquisition System Laboratory)<sup>4</sup> software was used to log the acceleration signals from the accelerometers onto a computer. The experimental apparatus is shown in Fig. 1.

It is important to understand how much of the soil vibration is transferred into an underground structure, and how the presence of a structure alters the vibration levels in its vicinity. The experimental study was aimed at understanding the relationship between the energy transferred to an underground structure and the impedance (product of material density and compression wave velocity) mismatch between the structure and the sand. Study in this area was carried out using two model tunnels, made of brass and plastic, placed in the sand tub. These materials were chosen as they exhibit large and small impedance mismatches with sand (Table 1).



Test	lnput	Brass	Plastic	Brass ppv/		
	PPV	PPV	ppv	Plastic ppv		
BVI	83	I∙40	∙80	0·78		
BV2	89	I∙50	∙75	0·86		
BV3	85	I∙30	∙50	0·87		
BV4	80	I∙35	∙60	0·84		
BV5	65	I∙25	∙40	0·89		
CVI	87	1·25	1·50	0·83		
CV2	95	1·22	1·50	0·81		
CV3	75	1·18	1·30	0·91		
CV4	78	1·10	1·40	0·79		
CV5	73	0·90	1·40	0·64		
Table I. Vertical peak particle velocity in model tunnels (BVI = B-set B, V = vibrating load, I = test I)						

# 3. VIBRATION SOURCES

#### 3.1. Impulse load

The impulse load was generated by dropping the 5 kg mass shown in Fig. 1 from a height of 40 mm. The drop hammer is controlled by means of a pneumatic switch. When the switch is off, low pressure is created in the vent connected to the hammer, and hence the hammer is held in a retracted position. When the switch is on, atmospheric pressure is let into the vent and the hammer falls under gravity.

## 3.2. Vibrating load

An electric motor with an eccentric rotating mass, as shown in Fig. 2, was used to produce the vibrations on the sand surface. The frequency of the electric motor was 50 Hz. The motor was attached to the same base plate as was used in the impulse load. Accelerometers were attached to the base plate, and typical horizontal and vertical acceleration time histories were recorded. The base plate experiences a peak particle acceleration of 3*g* in both the horizontal and the vertical directions. The horizontal and vertical acceleration profiles can both be approximated by a sinusoidal wave. Hence the component peak particle velocity can be estimated using equation (1),



Peak particle acceleration =  $2\pi f \times ppv$ 

where f is the frequency, and the component peak particle velocity (ppv) is 93.7 mm/s.

# 4. MODEL PREPARATION AND SOIL TYPE

Each model was prepared by pluviating the sand through air with the aid of a hopper. This was to make sure that the sand had the same void ratio and uniformly distributed packing in all the tests. LB 100/170 grade E dry sand was used in all the experiments (Table 2 provides the properties of grade E sand). A void ratio of 0.75 was aimed at in all the models. This corresponds to sand in a medium-dense state, thus minimising any densification that could occur during the course of the experiment.

## 5. MODEL TUNNELS AND EXPERIMENTAL SET-UP

Two model tunnels with the same geometry but made of different materials were used in the experiment. The model tunnels, with diameter 54 mm and length 320 mm, were made of brass and plastic (PVC), and weighed 0.720 kg and 0.115 kg respectively. Each model had two threaded 6 mm holes at right angles to the tunnel surface. Accelerometers were securely fastened into these holes to measure the vibrations transmitted into the tunnel from the soil.

Figure 3 shows the experimental set-up. Twelve accelerometers were used in the experiments: six were placed horizontally to measure the horizontal accelerations, and six were placed

Property	Value		
D <sub>10</sub> grain size: mm	0·095		
D <sub>50</sub> grain size: mm	0·14		
D <sub>90</sub> grain size: mm	0·15		
Specific gravity, G <sub>s</sub>	2·65		
e <sub>min</sub>	0·613		
e <sub>max</sub>	1·014		

Table 2. Properties of grade E sand

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vertically at exact mirror locations. Three sets of experiments were carried out: set A, to measure both horizontal and vertical acceleration in dry sand, and sets B and C, to measure the acceleration signal in the tunnels. Fig. 4 shows a plan view of the model during preparation for the set B experiment.



#### 6. DATA ACQUISITION AND FILTERING

The signals from the accelerometers were acquired and recorded using DASYLab software.<sup>4</sup> A sampling rate of 10 kHz per channel was used. The recorded data were processed before being used for analysis. The processing involved eliminating the initial zero error in the signals and filtering to remove high-frequency noise. A Butterworth filter was then used to eliminate frequency content above 500Hz. Accelerometer readings in mV were multiplied by the calibration factor of each accelerometer to obtain the acceleration in terms of *g* (i.e. 9·81 m/s<sup>2</sup>).

# 7. RESULTS: PEAK PARTICLE VELOCITY (PPV)

The results of experiment set A were used to confirm that the reflection of waves off the tub walls was insignificant. A compression wave velocity of 167 m/s was obtained using the elapsed time in signals between accelerometers ac4, ac5 and ac6. This is close to the theoretical prediction of 159 m/s at this depth (Table 3).

Figure 5 shows both the vertical and horizontal acceleration signals generated by the model tunnels under impulse load. It is clear that the plastic tunnel experiences higher peak acceleration in both the vertical and horizontal directions than the brass tunnel. Velocity-time profiles of the signals were obtained by integrating the acceleration signals using a MATLAB routine. Since the acceleration signals had a zero error that varied with time, the velocity profiles did not have a zero mean. However, this does not affect the determination of ppv, which can be obtained from each velocity profile graph as half the maximum fluctuation. Table 1 summarises the ppv experienced by the models. The mean of the ratio of vertical ppv in brass to that in plastic is 0.84. (The results of test CV5 have been ignored, as its ratio, 0.64, is well below the rest of the results: this could have been due to a loosened accelerometer.) Hence we can conclude that the vertical ppv in the plastic tunnel is 19% higher than that in the brass tunnel.

# 8. ENERGY CONTENT IN THE ACCELERATION SIGNAL: POWER DENSITY SPECTRUM

The damage to an underground structure depends not only on the amount of energy transferred into the structure but also on the frequencies at which the energy is transferred. The peak particle velocity experienced by the tunnels indicates the amount of energy transferred into the structure, but it does not provide the frequencies at which this energy is transferred. The power density spectrum of the acceleration signal can provide this information. MATLAB software was used to produce the power density spectrum of the acceleration signals. Figs 6 and 7 show the power spectrum of the vertical acceleration signal (ac11) in the sand, the brass tunnel and the plastic tunnel for impulse and vibratory loading respectively. The power spectrum of the vertical acceleration signal under vibratory loading in sand was very similar to that of the plastic tunnel, albeit with slightly higher magnitude, and hence for clarity it has not been included in Fig. 7.

The power spectrum of the vertical acceleration signal in sand, under impulse load, shows two distinct peaks at 75 Hz, and at 150 Hz, which corresponds to the natural frequency (see equation (7) in the Appendix) of the sand in the tub. It can be seen from Fig. 6 that the acceleration signals from both tunnels

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Material	ho: kg/m <sup>3</sup>	E: GPa	Velocity of pressure wave, V <sub>p</sub> : m/s	$\begin{array}{l} \text{Impedance I,} = \rho V_{\text{p}}:\\ \text{kg/m}^2 \text{s}  \times  10^3 \end{array}$
Sand	1525	-	159	242
Plastic tunnel	950	0.7	996	946
Brass tunnel	7500	110	4440	33300
Concrete	2400	25	3402	8165

Table 3. Impedance of different media (V<sub>p</sub> calculated using equations in Appendix)



under impulse load have their energy mainly in the frequency range 50–200 Hz, with peaks near 75 Hz and 150 Hz.

Under vibratory load, the brass tunnel tends to absorb energy at lower frequencies whereas the plastic tunnel absorbs at higher frequencies (Fig. 7). The vertical acceleration signal from the brass tunnel has the most energy near 100 Hz, whereas that from the plastic tunnel has the most energy near 150 Hz.

The above observations show that the frequency at which the vibrations are transferred into an underground structure depends not only on the source frequency but also on the material properties of the underground structure and the natural frequency of the soil layer in which the structure is located.

#### 9. WAVELET ANALYSIS

The power spectrum of a signal shows the distribution of energy in the signal with frequency. However, it cannot show whether specific frequency components are active at different times.





Harmonic wavelet analysis<sup>6–9</sup> makes it possible to understand the frequency content and the time duration for which a particular frequency component of the signal exists. Wavelet analysis of the vertical acceleration signals in plastic and brass was carried out using a MATLAB routine. Wavelet plots of the vertical acceleration signals in the plastic and brass model tunnels for impulse load are shown in Fig. 8(a) and Fig. 8(b) respectively. It can be seen that the 100 Hz frequency component of the acceleration signal in the brass tunnel lasts longer in the signal than the same frequency component of the acceleration signal in the plastic tunnel.

## **10. ENERGY TRANSFER INTO TUNNELS**

The vibration amplitude transferred into the plastic tunnel is higher than that transferred into the brass tunnel under both impulse and vibratory loads. This is quantified by the ratio of the peak particle velocity (vertical) in the brass model tunnel to that in the plastic tunnel, which is 0.84 (Table 2). The energy transferred into the model tunnel is proportional to the square of the peak particle velocity in the model tunnel. Hence:





The following relationship is proposed for the impedance mismatch ratio and the square of ppv ratio (i.e. ratio of the energy transferred).

$$\left(\frac{I_{\rm T} - I_{\rm s}}{I_{\rm b} - I_{\rm s}}\right)^{n} = \left(\frac{\rm Brass \ ppv}{\rm T \ ppv}\right)^{2}$$
$$= \frac{\rm Energy \ transferred \ to \ brass \ tunnel}{\rm Energy \ transferred \ to \ tunnel \ T}$$

where T is a model tunnel whose impedance is between that of sand and brass; I is the impedence (product of density and pressure wave velocity,  $pV_s$ );  $I_s$  is the impedence of sand and  $I_T$ is the impedence of tunnel T. Fig. 9 shows the experimental results and equation (3) with n = 0.05, 0.09 and 0.15. Note that all three lines pass through the point (1,1), which is a theoretical point (that is, the ratio of energy transferred is 1 when the ratio of impedance mismatch is 1). Equation (3) with n = 0.09 agrees with the mean of the experimental results. Fig. 9 can be used to predict the energy transferred into a material T at shallow depths (at low soil stresses). Hence, using Fig. 9, the ratio of energy transferred into a brass tunnel to that transferred into a concrete tunnel can be estimated as 0.88. Further experiments at higher stress levels and with different materials need to be done to validate and improve the proposed relationship (equation (3)).

# **II. GUIDANCE FROM BRITISH STANDARDS**

Guidance on the levels of ground-borne vibration that may cause damage to buildings is given mainly in two British Standards, BS 5228<sup>10</sup> and BS 7385.<sup>11</sup> Both of these give guidance on the ppv above which cosmetic damage could occur in buildings. British Standards have very little reference to underground structures. BS 7385 states: 'Structures below ground are known to sustain higher levels of vibration and are very resistant to damage unless in very poor condition.' BS 5228 gives threshold ppv values for underground services: a maximum ppv of 30 mm/s for transient and 15 mm/s for continuous vibrations. The standard fails to state the basis on which these levels were obtained, or the frequencies at which these limits apply with regard to underground structures.

As the present experiments were carried out in dry sand at low stress levels, it is not possible to extrapolate the results directly to clay or saturated soil. However, they do show the importance of understanding the frequency characteristics of waves into underground structures.

## 12. CONCLUSION

The tunnel lining has an important role to play in determining the amount of energy absorbed from ground-borne vibrations. The vibration amplitude transferred into the plastic model tunnel was shown to be higher than that transferred into the brass model tunnel under both impulse and vibratory loads. Under vibratory loading, the plastic tunnel appeared to absorb

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calculated by using equation (5)<sup>12</sup> and the relationship E = 2G(1 + v):

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$$G_{\text{max}} = \frac{100(3 - e)^2}{1 + e} (\sigma'_{\text{av}})^{0.5}$$

where  $G_{\text{max}}$  is the maximum dynamic shear modulus of the soil, *e* is the void ratio and  $\sigma'_{\text{av}}$  is the mean effective confining stress, given by

$$\sigma'_{\rm av} = \frac{\sigma'_{\rm v} + 2\sigma'_{\rm h}}{3}$$

Note that both  $G_{\text{max}}$  and  $\sigma'_{\text{av}}$  must be in MPa.

The natural frequency, *f*, of a soil layer can be calculated from



energy at higher frequencies (150–200 Hz) than the brass tunnel (100Hz). The experimental results show that the ratio of peak particle velocity (vertical) in the brass tunnel to that in the plastic tunnel is 0.84. Hence the ratio of energy transferred into the brass tunnel to the plastic tunnel, which is the square of the ppv ratio, is 0.71 (equation (3)). The higher the impedance mismatch between the tunnel lining and the sand, the lower the vibration energy transferred into the tunnel.

The above conclusions can form a basis for more research to expand knowledge in this field. Energy transfer into various tunnel linings such as precast concrete, shotcrete and steel can be investigated. Thorough study in this field will make it possible to understand and improve on the vibration limits set out by the present British Standards.

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# APPENDIX A

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The pressure wave velocity,  $V_p$ , in a material can be calculated by

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$$V_{\rm p} = \sqrt{\frac{E(1-v)}{
ho(1+v)(1-2v)}}$$

where *E* is Young's modulus,  $\rho$  is the density and *v* is Poisson's ratio for the material. The pressure wave velocity in sand is

where *H* is the thickness of soil layer,  $\rho$  is the density of soil, and  $G_{\rm av}$  is the average shear modulus of the soil given by the secant modulus at mid depth.

# REFERENCES

- 1. HEAD J. M. and JARDINE F. M. *Ground Borne Vibrations Arising from Piling*. Construction Industry Research and Information Association, London, 1992, CIRIA Technical Note 142.
- HILLER D. M. and BOWERS K. H. Groundborne vibrations from mechanized tunnelling works. *Proceedings of Tunnelling 97*, Institution of Mining and Metallurgy, London, 1997, pp. 721–735.
- 3. HOPE V. S. and HILLER D. M. The prediction of groundborne vibration from percussive piling. *Canadian Geotechnical Journal*, 1998, **37**, 700–711.
- 4. DASYLab (Data Acquisition System Laboratory), DASYTEC USA, 11 Eaton Road, PO Box 748, Amherst, NH 03031-0748, USA (www.dasylab.net).
- 5. MATLAB, The MathWorks Ltd, Matrix House, Cowley Park, Cambridge CB4 0HH, UK (www.mathworks.com).
- NEWLAND D. E. An Introduction to Random Vibrations, Spectral and Wavelet Analysis, Addison-Wesley, 1993, pp. 295–370.
- NEWLAND D. E. Harmonic Wavelet Analysis, Harmonic and Musical Wavelets. Cambridge University Engineering Department, 1993, Technical Report C-MECH/TR51.
- 8. NEWLAND D. E. Wavelet Analysis of Vibration. Part 1: Theory. Part II: Wavelet Maps. Cambridge University Engineering Department, 1993, Technical Report C-MECH/ TR54.

9. NEWLAND D. E. Signal Analysis by the Wavelet Method.

Cambridge University Engineering Department, 1995, Technical Report C-MECH/TR65.

- BRITISH STANDARDS INSTITUTION. Code of Practice for Noise and Vibration Control Applicable to Piling Operations. BSI, Milton Keynes, 1992, BS 5228 : Part 4.
- 11. BRITISH STANDARDS INSTITUTION. Guide to Damage Level

from Ground Borne Vibration. BSI, Milton Keynes, 1993, BS 7385: Part 2.

 HARDIN B. O. and DRNEVICH V. P. Shear modulus and damping in soils: design equations and curves. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 1972, 98, No. SM7, 667–692.

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