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SYNOPSIS Ground vibrations caused by impact were measured at two sites; one consisting of sand and the other of clay. Measurements were made at various radial distances from the impact location. The impact was produced by a weight falling either on to a plate or on to a rod partly driven into the ground, the latter case simulating pile driving on a small scale. When expressed in terms of scaled energy, the measured peak particle velocities were in reasonable agreement with some of the published data for clay sites but the agreement was poorer for sand sites. Several theoretical expressions were developed for peak particle velocity for both body and Rayleigh waves. All of these expressions yielded calculated velocities that were considerably greater than the values observed. It is considered that at least some of the disagreement could be attributed to energy losses.

INTRODUCTION

Field measurements of surface vibrations generated by a surface source such as pile driving, indicate that the peak particle velocity (v_o) is inversely proportional to the distance (D) from the vibration source (see Wiss (1967), D'Appolonia (1971), Attewell and Farmer (1973)). Some of the observed data is summarised in Figure 1. Because of the large scatter of observed points, several authors have preferred to locate an upper limit line rather than attempting to define a regression line through the plotted points. The Attewell and Farmer (1973) data for peak particle velocity for example is scattered up an order of magnitude below the upper limit line in Figure 1. Brewer and Viranuvut (1977) did produce a regression line based on the Brewer and Chittikuladilok (1975) data for Bangkok clay and this yielded peak particle velocities about one third of the values obtained from the upper limit line in Figure 1. The other regression line in Figure 1 is that based on the Gutowski (1978) data for piling through sandy silty soils.

The equations for the Gutowski and Brewer and Viranuvut regression lines respectively in Figure 1 are:

$$\text{peak particle velocity } (v_o \text{ mm/sec}) = 0.25\,(E)^{0.5}/D \quad (1)$$

and

$$v_o = 0.11\,(E)^{0.5}/D \quad (2)$$

both of which are considerably lower than the Attewell and Farmer upper limit value, namely:

$$v_o = 1.5\,(E)^{0.5}/D \quad (3)$$

CALCULATION OF PEAK PARTICLE VELOCITY

Theoretical expressions for the peak particle velocity of body and surface waves generated by pile driving operations have been developed by Attewell and Farmer (1977) and by Schwab and Bhatia (1985). They developed expressions for surface and body waves that related the peak particle velocity to the energy at the vibration source. These expressions, which actually contained some errors, were based on the assumption that all the energy was concentrated in the first wavelength of the vibration. If the errors are eliminated the relationships should read as follows. For body waves:

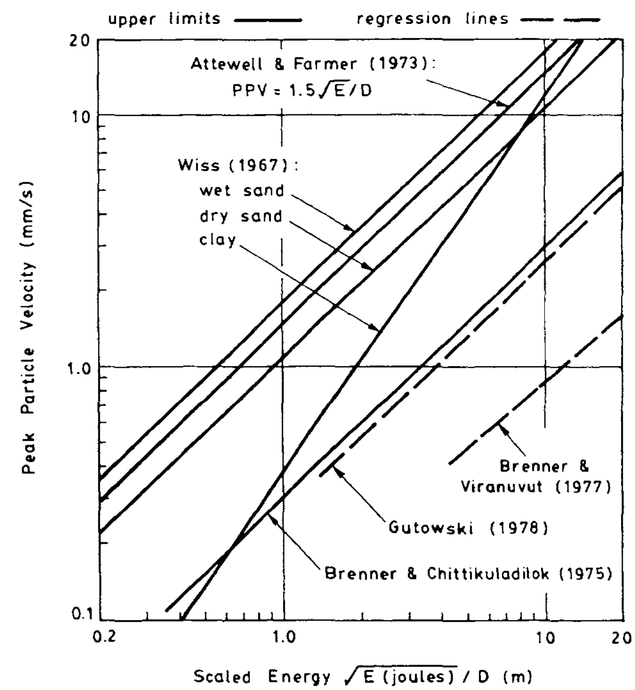

Fig. 1 Peak Particle Velocities caused by Pile Driving.

$$v_o = K_B E^{0.5}/D \quad (4)$$

where v_o = peak particle velocity at distance D
E = energy at the source
D = distance from the source
K_B = $(2/\pi\rho\lambda)^{0.5}$
ρ = mass density of the soil
λ = wave length of the vibration

and for surface (Rayleigh) waves:

$$v_o = K_S (E/D)^{0.5} \quad (5)$$

where K_S = $(2/\pi\rho\lambda\eta)^{0.5}$
h = distance below the ground surface within which the surface wave travels

Since the field observations are apparently consistent with the form of equation (4) both Attewell and Farmer (1973) and Schwab and Bhatia (1985) interpreted this to mean that the wave motion from pile driving is caused by body waves instead of surface waves.

If the body waves are taken to be compressional (P) waves the K_B term in equation (4) can be rewritten in a more convenient form:

$$K_B = (2f/\pi\rho v_p)^{0.5} \quad (6)$$

where f = vibration frequency
v_p = P wave velocity

For the surface (Rayleigh waves) the wave motion decreases with increasing depth below the ground surface but the following approximation may be used for h.

$$h \approx 1.6\lambda = 1.6 v_R/f \quad (7)$$

where v_R = Rayleigh wave velocity

The K_S term in equation (5) can then be re-expressed as:

$$K_S = (f/v_R) \times (0.8\pi\rho)^{-0.5} \quad (8)$$

FIELD TESTING

Pile driving was simulated by means of a falling weight system and testing was carried out at two sites. A sand site at Hallam Road consisted of a yellow fine sand layer extending to a depth of more than 5m. A clay site at Footscray Park consisted of a layer of soft to firm silty clay (Coode Island silt) overlying a firm to stiff silty clay (Fishermans Bend silt) of varying thicknesses to depths up to 30m. Based upon geophysical surveys and laboratory measurements the characteristics in Table 1 were selected as being representative.

TABLE 1 - Physical Characteristics of Field Sites

Site	P-wave velocity (m/s)	Rayleigh wave velocity (m/s)	Density (t/m^3)
Sand	200	100	1.9
Clay	900	300	1.4

The falling weight consisted of a 50kg steel ball and the drop height could be varied from 1.0m to 2.0m. The ball was positioned to fall on to a steel plate on the ground surface for impact from a surface source. For impact from an embedded source a smaller weight was positioned to fall on to the top of a post driven into the ground. Two posts were used namely a 26mm diameter timber post 0.82m long and a 16mm diameter steel post 0.62m long.

Measurements of peak particle velocity were made at intervals of 5m up to a distance of 50 from the impact source. The instrument used was a Gumoyo triaxial geophone with a 4.5 hertz natural frequency. Calibration of the instrument was carried out prior to field use. In conjunction with a Toshiba T5200/100 portable computer, a software package ENVIB, developed by Terrock Pty Ltd in Melbourne, was used to monitor and analyse the vibration signals. By this means particle velocities in the three co-ordinate directions and peak particle velocities were obtained in both the time and frequency domains.

ANALYSIS OF FIELD DATA

For analysis purposes the peak particle velocity and the frequency at which this occurred were extracted from the frequency domain data. For each observation two other relevant variables were recorded. These were the energy of the impact (E) and the distance (D) from the impact point to the geophone location where the velocity measurements were made. These two variables were combined into a term ($E^{0.5}/D$), widely referred to as the scaled energy.

For a surface source of impact the observed peak particle velocities have been plotted against the relevant scaled energy for both the sand and clay sites in Figure 2. The equations for the two regression lines drawn through the observations are given on the figure. For the embedded source the data is presented in Figure 3. Even though the observed points are widely scattered, regression lines have been drawn through them.

The regression lines in Figures 2 and 3 indicate much higher magnitudes of peak particle velocity than the lines obtained by Gutowski (1978) and Brenner and Viranuvut (1977) as shown in Figure 1. In fact the regression lines from this series of observations for both sand and clay sites lie in the general vicinity of the upper limit line for clay as proposed by Wiss (1967) (see Figure 1).

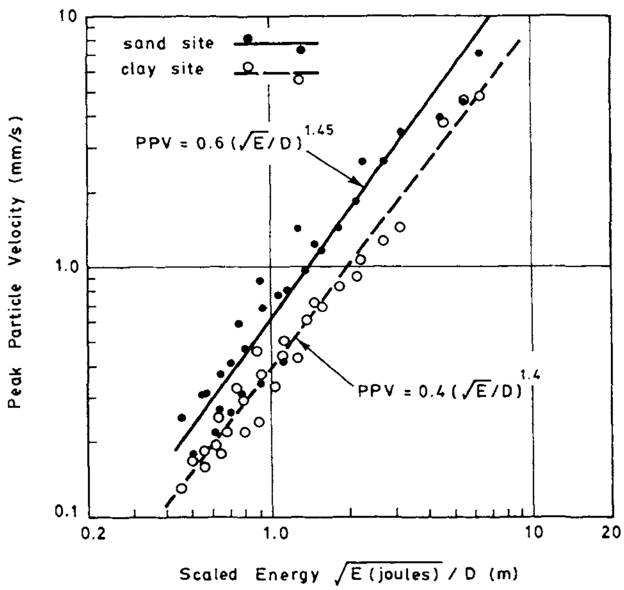

Fig. 2 Ground Motions – Impact from a Surface Source

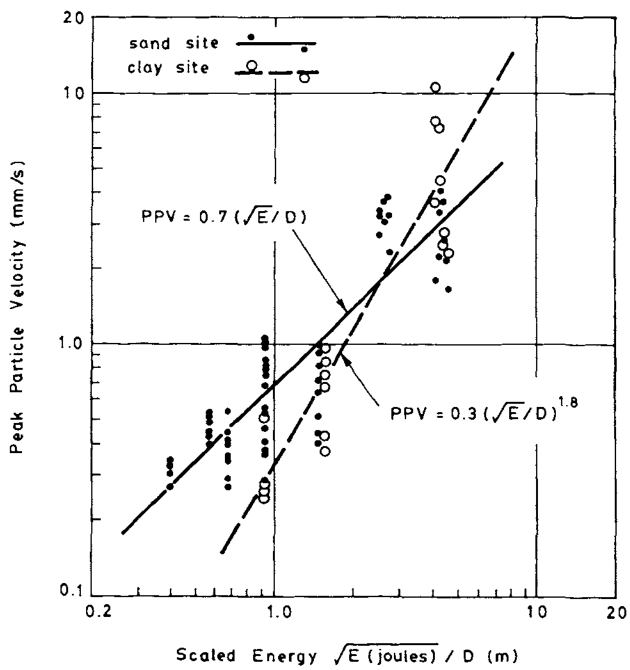

Fig. 3 Ground Motions – Impact from an Embedded Source

Attempts to calculate the peak particle velocities were made by making appropriate use of equations (4) and (5). By incorporating the site properties given in Table 1, equations (4) and (5) could be re-expressed as follows:

For body waves:

$$v_O = 1.29f^{0.5}(E^{0.5}/D) \text{ mm/s} \quad (9)$$
for the sand site, *and*

$$v_O = 0.71f^{0.5}(E^{0.5}/D) \text{ mm/s} \quad (10)$$
for the clay site

For Rayleigh waves:

$$v_O = 0.145fD^{0.5}(E^{0.5}/D) \text{ mm/s} \quad (11)$$
for the sand site, *and*

$$v_O = 0.056fD^{0.5}(E^{0.5}/D) \text{ mm/s} \quad (12)$$
for the clay site

In equations (9), (10), (11) and (12) the units of f are hertz, the units of E are joules and the D is in metres. Since a frequency term appears in all four of these equations the peak particle velocity was calculated for each particular observation. The frequency (f) that is used is that value at which the peak particle velocity occurs in the frequency domain. These principal frequencies were observed to decrease with increasing distance from the impact source. This is illustrated in Figure 4 which shows the decreasing trend in spite of the large scatter of observed results.

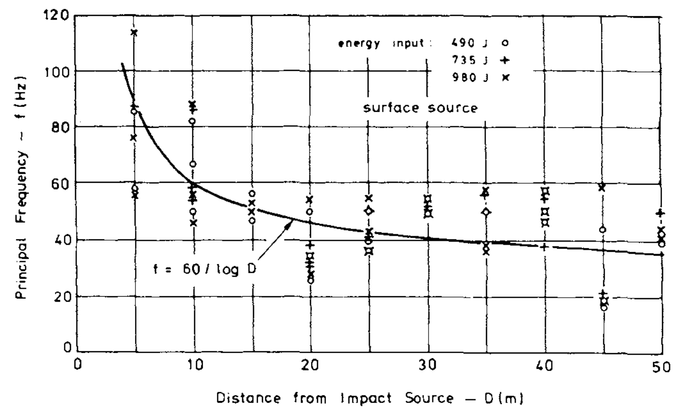

Fig. 4 Observed Principal Frequencies – Sand Site

The effects of the frequency (f) and distance (D) in equations (9), (10), (11) and (12) combine to yield predictions of velocity (v_o) which decreases with increasing distance. This is at least in qualitative agreement with observations as shown in Figure 5 for an embedded source of impact. If the four equations are used quantitatively the calculated peak particle velocities can be compared directly with the regression lines based on the observations in Figures 2 and 3. This is done in Figure 6 for the clay site and shows that equations (10) and (12) yield calculated values of peak particle velocity that are greater that the observed values, particularly at low magnitudes of scaled energy. It should be noted that the calculations are based on individual observations so it is to be expected that a plot of the calculated peak particle velocities will exhibit a scatter. The hatched area in Figure 6 encloses this scatter.

For the sand site the comparison is shown in Figure 7. In this case the scatters for the calculated Rayleigh wave and body wave peak particle velocities were distinctly separated so they have been shown separately as hatched areas. These calculated values are seen to be more than an order of magnitude greater than the observed values The reason for this very large overprediction of peak particle velocity is not clear but the most likely cause would appear to be the assumption that all the energy from the impact was concentrated in the first wavelength of the vibration as mentioned above.

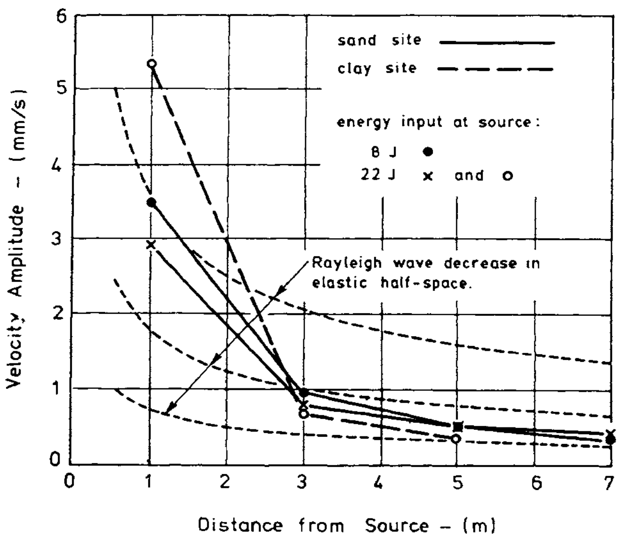

Fig. 5 Velocity Amplitude Decrease from an Embedded Source

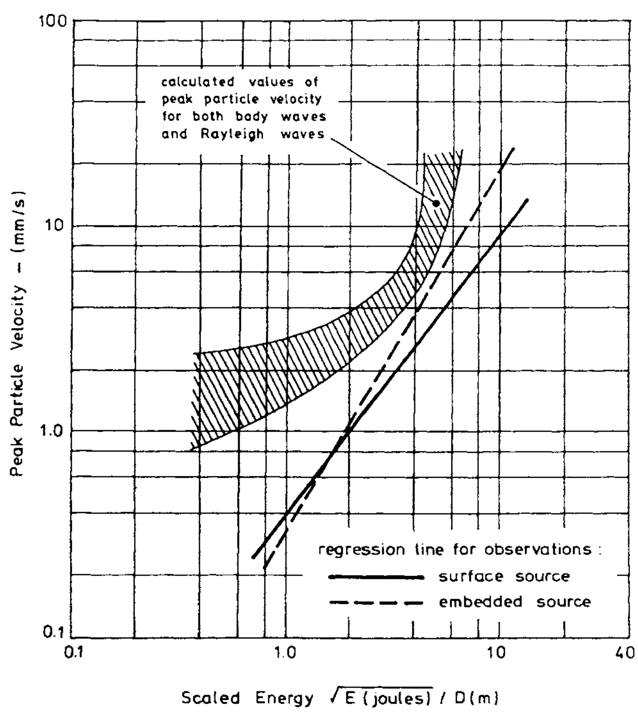

Fig. 6 Calculated and Observed Vibrations – Clay Site

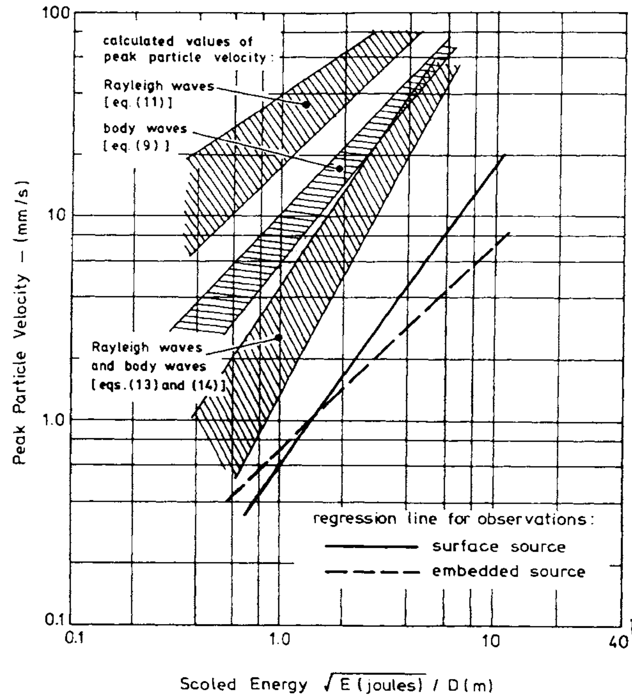

Fig. 7 Calculated and Observed Vibrations – Sand Site

An attempt was made to improve the calculation of peak particle velocity by allowing for its variation with time at a particular location and its variation with distance from the source of impact at a particular time. It was assumed that the impact energy was distributed over all wave lengths of the vibration extending from the source to the wave front. It was further assumed that the maximum peak particle velocity occurred a short distance back from the wave front, the envelope of peak particle velocities following a curve of the type shown in Figure 8.

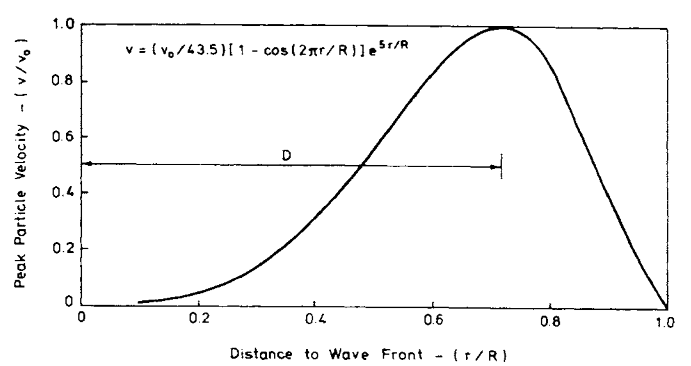

Fig 8 Proposed Variation in Peak Particle Velocity with Distance from Impact Source

The equations for peak particle velocity (v_o) derived from this attempt for the sand site are:

$$v_O = (350/D\, f^{0.5})\,(E^{0.5}/D) \text{ mm/s} \quad (13)$$

for body waves, *and*

$$v_O = (19.9/D^{0.5})\,(E^{0.5}/D) \text{ mm/s} \quad (14)$$

for Rayleigh waves

Calculated values of peak particle velocity for the sand site using equations (13) and (14) are shown by the hatched area in Figure 7. While this represents a considerable improvement compared with calculations using equation (9) and (11), the calculated peak particle velocities are still much greater than those observed, particularly at large magnitudes of scaled energy. For the clay site there was relatively little improvement over the calculated values already presented in Figure 6. Clearly the calculation of peak particle velocity requires further investigation.

CONCLUSIONS

Observed peak particle velocities at a sand and at a clay site at various distances from a source of impact simulating pile driving were found to be of greater magnitude than those previously reported in the literature. In fact the regression lines from the observations were in the general vicinity of the upper limit line for clay originally proposed by Wiss, when the results are expressed in terms of scaled energy. Attempts at calculating peak particle velocity were not very successful and generally yielded values considerably greater than those observed.

REFERENCES

Attewell, P.B. and Farmer, I.W. (1973), "Attenuation of Ground Vibrations from Pile Driving", Ground Engineering, pp. 26 - 29.

Brenner, R.P. and Chittikuladilok, B. (1975), "Vibration from Pile Driving in the Bangkok Area". Geotechnical Engineering, Vol. 6, No. 2, pp 167 - 197.

Brenner, R.P. and Viranuvut, S. (1977), "Measurement and Prediction of Vibrations generated by Drop Hammer Piling in Bangkok Subsoils", Proc. Fifth Southeast Asian Conf. on Soil Engineering, pp. 105 - 119, Bangkok.

D'Appolonia, D.J. (1971), "Effects of Foundation Construction on Nearby Structures", Proc. 4th Panamerican Conference on Soil Mech. and Found. Eng., Vol 2, pp 189 - 235, Puerto Rico.

Gutowski, T.G. (1978), "Ground Vibration from Cut-and-Cover Tunnel Construction", Sound and Vibration , April 1978, pp. 16 - 22.

Schwab, J.P. and Bhatia, S.K. (1985), "Pile Driving Influence in Surrounding Soil and Structures", Civil Engineering for Practicing and Design Engineers, Vol. 4, No. 8, pp 641 - 684, Pergaman Press Ltd.

Wiss, J.F. (1967), "Damage Effects of Pile Driving Vibrations", Highway Research Record No. 155.