VIBRATIONS ON A MODEL PILE IN SOFT CLAY

P. J. MOORE* and B. K. G. CROSSLEY**

ABSTRACT

The elastic buckling characteristics of a slender model pile embedded in soft clay have been investigated for both static and vibratory loading conditions. The load-rotation behaviour was studied for a static eccentric load. Comparative tests were carried out with vertical vibrations imposed directly on the pile in order to simulate the field situation in which the vibrations originate from a pile supported structure. It was found that the pile buckling characteristics as measured by both the ultimate load and the elastic critical load were not significantly altered by the presence of vibrations. From considerations of a possible scaling law from model to prototype it was found that different conclusions regarding possible prototype behaviour could be drawn depending upon the method used for the measure of vibration severity. Measurements of field vibrations produced by traffic were found to yield quite low vibration severities, but it is possible that more severe vibrations could occur in other field situations.

Key words: model tests, piles, vibrations, pile foundations, pile loading tests, models, foundations

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INTRODUCTION

The buckling behaviour of slender piles embedded in soft cohesive soils has been examined extensively (Refs. 1, 2, 3) both theoretically and experimentally for static loading conditions. There has however been relatively little investigation of the effects of vibration on the pile buckling characteristics. While it was recognized that cohesionless soils were very sensitive to the effects of vibration it was often assumed that vibration had no significant influence on cohesive soils.

The influence of vibrations passing through the ground on the buckling behaviour of a slender pile was investigated by Moore and Irwin (Ref. 4). They reported no significant effect by vibrations of magnitudes normally encountered in the field. In this study the vibrations were considered to originate from a source external to the structure or its supporting piles.

In this study the effects of vibrations which would originate from a structure (such as traffic vibrations on a pile supported bridge) supported by the piles have been examined. As in the companion investigation (Ref. 4) it was considered that the simplest way of isolating the effect of vibration on the buckling behaviour of a slender pile embedded in soft clay was to conduct comparative static and vibratory tests on an eccentrically loaded

* Reader in Civil Engineering, University of Melbourne, Parkville, Victoria, Australia.

** Engineer, Maunsell and Partners, Melbourne, Australia.

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pile.

ASSESSMENT OF VIBRATION INTENSITY

One of the difficulties associated with investigations aimed at the evaluation of the effects of vibrations is the lack of widely accepted criteria for the assessment of vibration intensity. In

Fig. 1. Human sensitivity to continuous vertical vibration (Reiher-Meister scale)

in which a = maximum acceleration amplitude
 ω = frequency of vibration (Hz.)

For comparative purposes this scale is presented in Fig. 2 on a type of plot similar to that used for the Reiher-Meister scale in Fig. 1. A further criterion which is based upon Zeller's Z value has been suggested by Steffens (Ref. 9). This is the vibrar unit which is illustrated in Fig. 3 in which

$$\text{strength in vibrar units} = 10 \log_{10} (10Z)$$

FIELD VIBRATION MEASUREMENTS

A number of vibration measurements were made on prototype structures in order to assess the range of vibration severities within which the laboratory tests should be performed. Two accelerometers were obtained for these measurements, a Schaevitz servo force balance accelerometer and a Kistler piezoelectric. The specifications for these accelerometers are given in Table 1. The two instruments were intended to act as a check on each other and the Kistler was intended to provide more reliable measurements of any high amplitude and

in the evaluation of human response to vibrations the Reiher-Meister (Ref. 5) scale (Fig. 1) is widely applied although Dieckmann (Ref. 6) has proposed a different set of criteria. He used acceleration amplitude as the criterion for vertical frequencies below 5 Hz., velocity for frequencies between 5 Hz. and 40 Hz. and displacement for higher frequencies. Criteria similar to those proposed by Dieckmann have been adopted for the German Standard (D. I. N. 4025—1958).

For the evaluation of the response of structures to vibrations velocity criteria have been used by a number of workers and there is a reasonable level of agreement between their various proposals. These criteria were intended mainly for transient vibrations (Ref. 7) such as those produced by blasting, pile driving or passing traffic. For continuous vibrations Zeller (Ref. 8) has proposed a scale of structural damage as a function of "Zeller's Strength of Vibration" (Z) where

$$Z = \frac{a^2}{\omega} \text{ cm}^2/\text{sec}^3$$

Fig. 2. Intensity scale for continuous vibrations—effect on buildings or persons

Fig. 3. Intensity scale for continuous vibrations in terms of the vibrar unit

Table 1. Accelerometer specifications

BRAND NAME	SCHAEVITZ	KISTLER
Model No.	LSB E 16-1	818
Type	Servo-force	Piezoelectric
OPERATING SPECIFICATIONS		
Range	$\pm 1g$	$\pm 250 g$
Natural frequency	75 c.p.s.	not stated
Mounted Resonant Frequency	not stated	35,000 c.p.s.
Sensitivity	5 V/g	10 mV/g
Max. Transverse Sensitivity	.04%	1.6%
Amplitude Linearity	$\pm 0.05\%$ full scale	$\pm 0.1\%$ max. deviation (2 to 4,000 c.p.s.)
Frequency Response	$\pm 5\%$ to 60 c.p.s.	$\pm 3\%$ max. deviation to 20 kc.
Damping Ratio	0.61	0.02
MECHANICAL SPECIFICATIONS		
Weight	approx. 3 oz.	0.7 oz.
Size	2.0" $\times$ 1.1" $\times$ 1.2"	0.5" Hex. $\times$ 0.9"
Seal	Hermetic	Epoxy

high frequency vibrations. The Schaevitz with its natural frequency of 75 c.p.s. could provide accurate measurements of acceleration at frequencies up to about 60 c.p.s. The Kistler could provide accurate measurements of acceleration at frequencies up to 20,000 c.p.s.

The excitation for the Schaevitz accelerometer was provided by a Hewlett-Packard and a Heathkit DC power supply. The recording system consisted of a Tekronix type 564 storage oscilloscope in conjunction with a mounted camera.

Measurements of vertical and horizontal vibrations were made at several locations on Kings Bridge and at one location on the Flinders Street Overpass in Melbourne. The locations are shown in Figs. 4 and 5. The accelerometers had to be rigidly attached to the structure so as not to invalidate the vibration measurements. It was essential that these attachment devices permitted measurement in three mutually perpendicular directions and did not damage the bridges. An aluminium mounting adaptor which could be cemented firmly to the bridge structure, and to which the accelerometers could be screwed was devised. An analysis of the adaptor as a cantilever yielded a natural frequency of approx. 5,500 c.p.s. which was much greater than the expected vibration frequency range.

Vibration measurements were taken during peak hour traffic in an attempt to detect the

Fig. 4. Vibration measurement points—Kings Bridge

most severe vibrations. Typical results of these measurements are shown in Fig. 6. In cases where the vibration was not a simple wave form the amplitude and frequency components were estimated using the envelope method as described by Manley (Ref. 10). For frequencies higher than the range of the Schaevitz accelerometer the amplitudes were corrected according to the calibration curve in order to give an approximate measure of the actual amplitude. The calibration which is simply the response curve for a damped mass-spring system is reproduced by Moore and Irwin (Ref. 4). Generally the Kistler accelerometer indicated slightly larger vibration amplitudes compared with the Schaevitz. Because of some irregularities that were experienced with the Kistler greater reliance was placed on the results from the Schaevitz and the latter instrument was used for the vibration measurement record.

A summary of the maximum acceleration amplitudes measured on both bridge structures has been presented in Fig. 7. In order to determine the vibration severity that these acceleration amplitudes represent the data has been converted into maximum velocity amplitudes and these are plotted in Fig. 8. These plots indicate that the most severe vibrations were measured in the vertical direction. While these Figures may indicate the level of vibration severity that may be reached in normal heavy traffic it certainly does not follow that these maxima cannot be exceeded.

Fig. 5. Vibration measurement points—Flinders St. overpass

(a) SITE 2 - MID - SPAN - VERTICAL VIBRATION

(b) SITE 1 - ON FOUNDATION PILES - VERTICAL VIBRATION

Fig. 6. Typical vibration records—Kings Bridge

Low frequencies of the order of 5 c.p.s. were observed at midspan in the vertical direction and these vibrations are probably related to the natural frequency of the span itself since the calculated natural frequency was of this order of magnitude. Frequencies in the other directions were generally higher but no particular trend or relationship emerged from the results. The highest vibration frequencies of around 200 c.p.s. were produced by trams while vehicular traffic yielded dominant frequencies below 40 c.p.s.

The records confirmed the transient nature of the individual traffic vibrations with maximum amplitudes occurring as a single peak or over a time interval of one or two seconds maximum. Vibrations decayed quickly as shown in Fig. 6, in which the vibrations from two trucks, two seconds apart, are shown. In comparing the velocity amplitudes with the velocity criteria mentioned above it seems that normal traffic does not produce very severe vibrations.

Fig. 7. Measured vibrations at Kings Bridge and Flinders St. overpass—maximum acceleration amplitudes

Fig. 8. Maximum velocity amplitudes of measured vibrations at Kings Bridge and Flinders St. overpass

EXPERIMENTAL ARRANGEMENT FOR PILE BUCKLING TESTS

In order to examine the effects of vibrations on pile buckling behaviour comparative static and dynamic tests were carried out on a small slender pile. This pile consisted of a strip of high tensile spring steel measuring 31 in. $\times$ 15/16 in. $\times$ 1/16 in. The pile was located inside a drum of soil, the drum measuring 22 in. in diameter and 30 in. deep. A slot was cut centrally in the base of the drum to allow the pile to pass through to a vee-notch mounted on a vibrator (Fig. 9). The vibrator provided the support for the pile, the drum being supported independently on a wooden frame.

The pile projected two inches above the surface of the soil to provide clearance for measurement of head rotation. To ensure initial pile straightness the soil was placed with the pile in tension. Following the completion of soil placement the pile was pushed into the vee-notch mobilizing shear stress along the length of the pile.

Eccentric loading was applied to the pile through a proving ring by means of a screw jack pushing against a reaction frame. A horizontal bar screwed to the pile loading head permitted pile head displacements and rotations to be measured with two vertical dial gauges touching the ends of the bar.

Vibrations were applied to the bottom of the pile by means of a rotating mass oscillator. The frequency of the oscillator could be varied up to 40 c.p.s. and the vibration amplitude could be varied by altering the number of rotating masses. Since the field vibration measurements indicated that the most severe vibrations were in the vertical direction, this direction, was chosen for the vibrations to be applied to the pile.

Vibration amplitude and frequency measurements were made with the Schaevitz acceler-

Fig. 9. Sketch of pile tensioning arrangement at pile toe during placing of soil

ometer attached to the vibrator. Instead of measuring the vibration input for each dynamic test the speed of the electric motor of the vibrator was calibrated with the intensity as illustrated in Table 2. The four intensities of vibration shown in this table were those at which the dynamic tests were carried out.

The soil used in the laboratory tests was a clayey silt from South Melbourne. The water content at which the soil was placed was around 31% to 32% since these were the lowest water contents at which small fluctuations in water content had relatively small effects on soil strength. The soil was placed in layers four inches thick around the pile. Each layer was compacted by two blows from a 10 lb. hammer falling 18 in. on to a shaped wooden board. Two coverages over the whole soil surface were provided. When the drum was filled with soil the surface was trowelled smooth and covered with a wet cloth to minimize loss of moisture by evaporation.

STATIC AND DYNAMIC LABORATORY TESTS ON PILE

The pile was loaded with an eccentricity of 1/4 in. in about 15 increments with readings

Table 2. Amplitudes, human response and intensity of vertical vibrations applied to model pile

SPEED SETTING			33	43	53	63
VERTICAL VIBRATION	FREQUENCY (c.p.s.)		15	20	25	30
	ACCELERATION (±g)		0.11	0.18	0.28	0.50
	VELOCITY (±in./sec.)		0.45	0.55	0.69	1.02
	DISPLACEMENT (±in.)		0.0048	0.0044	0.0044	0.0054
HUMAN RESPONSE	REIHER-MEISTER		Unpleasant	Painful	Painful	Painful
	DIECKMANN		Unpleasant	Very Unpleasant	Very Unpleasant	Very Unpleasant
VIBRATION INTENSITY AND POSSIBLE STRUCTURAL DAMAGE	‘ZELLER’ CRITERIA	Z (cm. ² /sec. ³)	800	1600	3000	8000
		Strength	Fairly Strong-Small Cracks	Strong-Danger Zone	Strong-Danger Zone	Very Strong-Serious Cracking
	‘VIBRAR’ CRITERIA	Vibrar Units	39	42	45	49
		Strength	Strong-Cracks in Rendering	Heavy Vibration-Wall damage	Heavy Vibration-Wall damage	Heavy Vibration-Wall damage
	‘VELOCITY’ CRITERIA	Crandell	Safe	Safe	Safe	Safe
		U.S. Bureau of Mines	Unsafe	Unsafe	Unsafe	Unsafe

Fig. 10. Typical load-rotation curve for model pile

Fig. 11. Effect of moisture content on ultimate load

of head rotation being taken throughout the test. Following the application of a load increment further head rotation was observed together with load relaxation. When no decrease in load was observed for a period of two minutes the pile was considered to be in equilibrium. A typical load-rotation curve is shown in Fig. 10. Identical testing procedures were followed for tests with and without vibration. For the dynamic tests four different vibration intensities were used as shown in Table 2. Higher ultimate loads were observed in tests 1 and 11 and the reason for this appears to be because of the lower soil moisture contents as shown in Fig. 11.

The effect of vibration intensity on the ultimate load is shown in Fig. 12. In this figure three measures of vibration intensity have been used. These are Zeller's strength of vibration, vibrar units and velocity amplitude. Excluding tests 1 and 11 from consideration as these have been explained in terms of moisture content there is seen to be no significant change in ultimate load with increases in vibration intensity. This conclusion is independent of the measuring system used for the vibration intensity.

A further measure of pile buckling characteristics may be obtained from the elastic critical load. This load may be obtained from the initial slope of the Southwell plot of pile head rotation θ against θ/P as has been demonstrated by Timoshenko and Gere (Ref. 11) and by Hoadley (Ref. 12). The elastic critical loads which are extracted from the Southwell plots have been expressed as a function of velocity amplitude in Fig. 13. This plot indicates that there is no significant variation in the elastic critical load as the vibration severity increases. This same conclusion can be drawn regardless of the measure that is used for vibration severity.

Fig. 12. Variations of ultimate load with vibration severity

Fig. 13. Effect of vibration on the elastic critical load

PROTOTYPE SCALING

The conclusions drawn in the previous section refer to a small scale pile. In order to ascertain the applicability of these conclusions to the prototype situation it is necessary to consider a possible scaling law. In the absence of a generally accepted scaling mechanism Moore and Irwin (Ref. 4) have developed a relationship which indicates that dynamic similitude between model and prototype can be maintained if the vibration velocities for each are identical. This means that if the velocity amplitude is used as a measure of vibration severity then the conclusions that can be drawn from model tests apply similarly to the prototype.

If Zeller's Strength of Vibration (Z) is used as the measure of vibration severity then the ratio of the model to prototype values of Z may be found by further development of the scaling mechanism above:

$$\begin{aligned} \frac{Z_m}{Z_p} &= Z_r = \frac{(a^2/\omega)_m}{(a^2/\omega)_p} \\ &= \frac{(L_m T_m^{-2})^2}{T_m^{-1}} \bigg/ \frac{(L_p T_p^{-2})^2}{T_p^{-1}} = \frac{(L_r T_r^{-2})^2}{T_r^{-1}} \\ &= L_r^2 T_r^{-3} = (L_r T_r^{-1})^2 T_r^{-1} \end{aligned}$$

where the m and p subscripts refer to model and prototype respectively and the subscript r refers to the ratio.

$=T_r^{-1}$ since the velocities in both model and prototype are the same

$=L_r^{-1}$ since the length and time scales are equal

This shows that the ratio of prototype to model vibration severities as measured by Zeller's Strength of Vibration is equal to the ratio of model to prototype lengths. This means that a much more severe vibration severity would have to be used in model experiments in order to evaluate the effect on the prototype. This finding suggests that different answers may be obtained depending upon the method used for the measure of vibration severity.

CONCLUSIONS

From the results of the field vibration measurements and tests described the following concluding remarks could be made:

- (a) The measured vibrations originating from traffic on pile supported structures were not of very high severity.
- (b) The elastic buckling characteristics of a slender model pile are not significantly affected by vertical vibrations originating from a pile supported structure.
- (c) The validity of (b) to the prototype situation depends upon the quantity that is used to indicate the vibration severity as well as the relevant scaling law.

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NOTATION

- a =acceleration (ft./sec.²)
- L_r =ratio of length in model to that in prototype
- P =pile axial load (lb.)
- T_r =ratio of time in model to that in prototype
- v =velocity amplitude (in./sec.)
- x =displacement amplitude (in.)
- Z =Zeller's strength of vibration (cm.²/sec.³)
- θ =pile head rotation (radians)
- ω =frequency (cycles/sec.)

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