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SYNOPSIS An experimental and theoretical study has been carried out to examine the effects of vibration frequency and amplitude as well as magnitude of static applied load on the uplift capacity of piles driven into a sandy soil. The theoretical solution was developed using a lumped parameter model with viscous damping. The results, both theoretical and experimental, indicate that the displacement amplitude required to cause uplift failure of the pile, decreases as the vibration frequency increases. This trend was shown to be significantly dependent upon the natural frequency of the pile-soil system and to a lesser degree, upon the damping ratio. At low vibration frequencies, observed and calculated vibration amplitudes required to cause uplift failure were found to be in approximate agreement. The application of a surcharge pressure to the sand surface was found experimentally to increase the uplift capacity of the pile under vibration.

INTRODUCTION

Much theoretical and experimental work has been carried out in relation to the evaluation of resisting capacity of a pile when subjected to static uplift forces. It appears that relatively little work has been done in evaluating uplift pile capacity when vibratory loads are involved. These vibratory loads could be derived from wind loading effects, machinery or earthquake vibrations. Many studies of the vibratory response of piles have been performed, for example, Maxwell et al (1969), Nogami and Novak (1976), Novak and Grigg (1976), Davis and Dunn (1974), Oweis (1977) and Satter (1976), but the attention of these authors was generally directed towards compression piles. Doubt has been expressed about the capabilities of piles maintaining the mobilized skin friction when subjected to vibratory tensile load, particularly when the pile has been driven into sandy soil. Under such circumstances, Broms and Silberman (1964) have expressed the view that very conservative values of skin friction should be used for design. This view is consistent with the findings from the experimental work of Paunescu (1964) who found that the pullout resistance of a pile during vibration was significantly less than the static pullout resistance. Paunescu however did not examine the effects of various vibration frequencies and amplitudes. A study of some of these effects on pile uplift capacity is described in this paper.

ANALYTICAL MODEL

A simple analytical model was chosen for the theoretical study of the effects of vibrations on pile pullout behaviour and is illustrated in Fig. 1. The pile of mass m (kilograms) is buried in soil and is subjected to a statically applied tensile (upward) force F (newtons). The resisting effect of the surrounding soil is represented by a spring (constant k (newtons/metre)) and viscous dashpot (damping coefficient c (newton sec./metre)). The pile pullout resistance T (newtons) is represented by the slide in Fig. 1. Static failure of the pile occurs when forces F and T are equal. If F is less than T, failure may occur if the pile is subjected to a vertical vibration represented by

$$z = z_o \sin \omega t \tag{1}$$

where z_o is the vertical displacement amplitude (metres)
ω is the vibration frequency (radians/sec.)

Under these conditions failure occurs when the sum of the force F and the dynamic upward force transmitted through the spring-dashpot unit is equal to the sliding force T. The dynamic force (P (newtons)) may be expressed in terms of the spring and damping constants

$$P = kz + c\dot{z} \tag{2}$$

It may be shown that the maximum value of P is reached when

$$\tan \omega t = \omega_n / 2D\omega \tag{3}$$

where ω_n is the natural frequency = $(k/m)^{1/2}$
D is the damping ratio = c/c_c
c_c is the critical damping coefficient = $2(km)^{1/2}$

The maximum value of P may be obtained by substitution of equation (3) into equation (2) to give

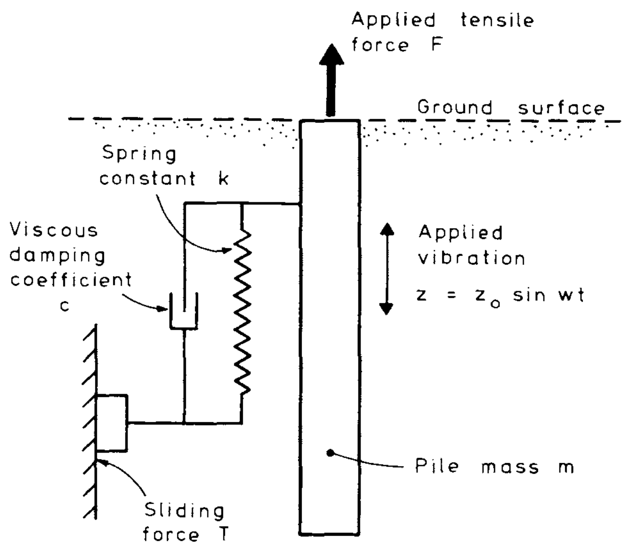

Fig. 1. Proposed Model for Vibrating Tensioned Pile

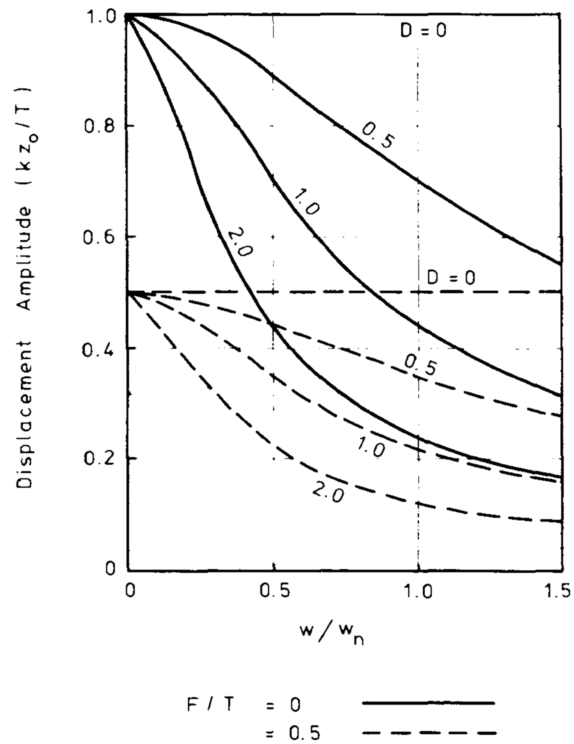

Fig. 2. Displacement Amplitude Required to Cause Pile Failure

$$P_{max} = kz_o \; [1 + (2D\omega/\omega_n)^2]^{\frac{1}{2}} \qquad (4)$$

As previously mentioned failure of the pile occurs when

$$P_{max} + F = T \qquad (5)$$

This failure condition may be re-expressed as

$$kz_o/T = [1 - (F/T)] \; [1 + (2D\omega/\omega_n)^2]^{-\frac{1}{2}} \qquad (6)$$

Equation (6) provides a means of determining the magnitude of the displacement amplitude of vibration (z_o) required to cause pile failure by uplift. Fig. 2, which graphically illustrates equation (6), shows that the required displacement amplitude decreases as the vibration frequency increases, or as the damping ratio increases, or as the applied tensile force (F) increases.

EXPERIMENTAL PROGRAM

The tests were carried out on piles that were pushed into a container of dry sand. The sand used was a uniform quartz sand with a median grain size of 1.0 mm and a uniformity coefficient of 1.4. In order to facilitate reproducible test results it was necessary to prepare a sand mass as homogeneous as possible using a technique by which a range of densities could be obtained. Kolbuszewski (1948) has shown experimentally that a range of densities can be reproduced by allowing the sand to fall as a rain (pluvial compaction). He found that the major factors determining the density of the sand mass were the intensity of the rain and the height of fall. The technique described by Jacobsen (1976) was used to guide the design and construction of a 1 m square sand raining device, which was then used to prepare a 1m x 1m x 0.8m sand volume. Two sand densities were used in the tests; 1.48 Mg/m^3 and 1.55 Mg/m^3, representing relative densities of 43% and 77% respectively.

Four steel piles were used in the tests with diameters between 22 mm and 34 mm and 0.63 m long. Two of the piles had smooth surfaces and two were roughened by covering the steel shaft in Araldite and rolling the shaft in sand (Thompson 1971). The pile was attached to the aluminium pile loading apparatus (Fig. 3), which was mounted over the sand bin. To this apparatus were fixed the electro-magnetic vibrator and a Sangamo D91 load cell. The pile was then slowly pushed into the sand mass by means of a gearing mechanism connected to the top of the pile loading apparatus.

A counterweight for the pile, load cell, vibrator and aluminium frame was provided by means of a dead-weight system via pulleys. Before testing commenced a net uplift force was applied to the pile by means of the dead-weight system. A low amplitude vibration was then applied to the pile through the electromagnetic vibrator. The amplitude and frequency of the vibration were controlled by means of a HP sine wave

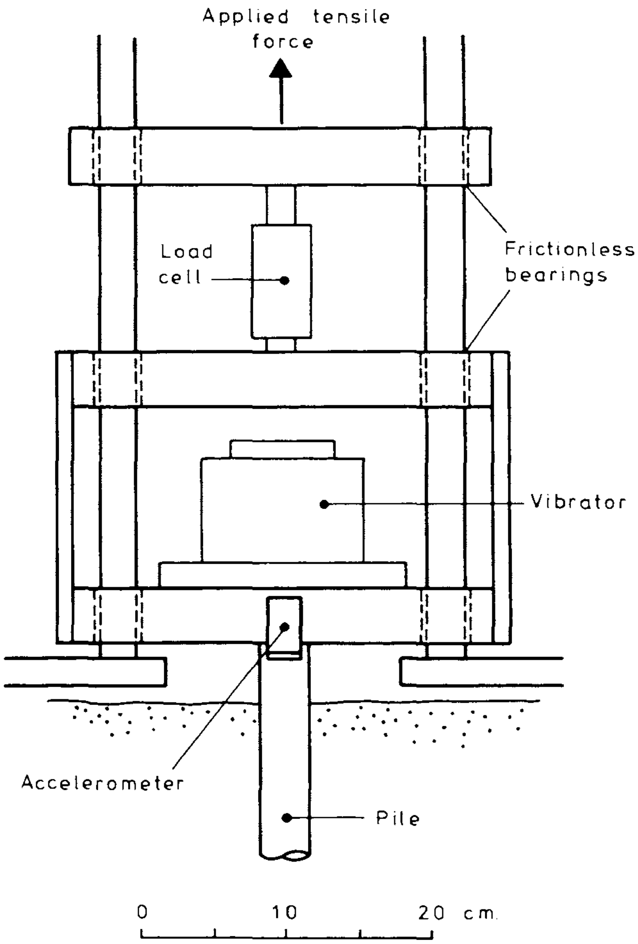

Fig. 3. Pile Loading Apparatus

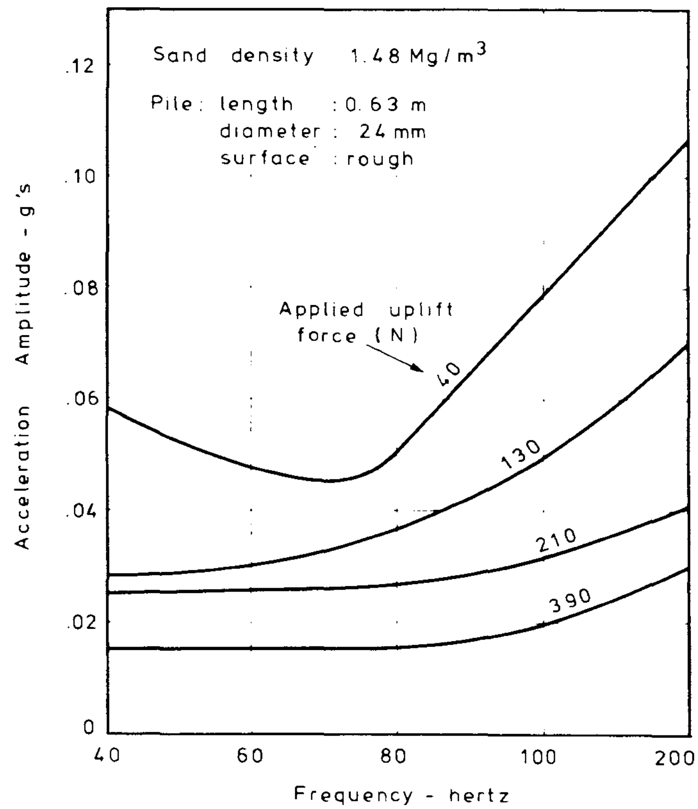

Fig. 4. Observed Amplitudes Causing Uplift Failure

generator. The vibration was monitored with a Sundstrand Servo Accelerometer 303GA which was firmly attached to the top of the pile. The 28 volt excitation voltage for the accelerometer was provided by a HP6215 power supply. The natural frequency of the accelerometer was 760 hertz, which is much greater than any of the test frequencies. The read out equipment consisted of a Tektronix Dual Beam Oscilloscope 502A. The vibration amplitude was gradually increased until the commencement of pile pullout failure became evident. On subsequent tests the procedure was repeated at different vibration frequencies. Most of these tests were repeated several times to provide a reliable indication of the vibration amplitude at which continuous upward movement of the pile commenced.

TEST RESULTS

Plots of the experimental data are shown in Figs. 4, 5, 6 and 7. For a particular vibration frequency and statically applied uplift force, these figures indicate the magnitudes of the acceleration amplitude of vibration that were required to cause pile failure by uplift. The data from over 60 tests was used to prepare Fig. 7. This particular figure indicates the large scatter in the experimental results through which the average curve has been plotted as a heavy line.

From an examination of the test data the following comments could be made.

(a) In most cases the acceleration amplitude required to cause uplift failure of the pile increased as the vibration frequency increased.

(b) For the smooth pile surface the influence of the initial placement density of the sand was quite marked. For comparison with Fig. 6, no vibration tests with the lower density sand could be performed since uplift occurred following application of the static uplift force.

(c) The application of a surcharge pressure to the surface of the sand deposit generally had the effect of raising the magnitude of the acceleration amplitude required to cause failure of the rough pile.

(d) The uplift resistance of the rough pile under the effects of vibration appears to increase as the pile diameter increases, but the effect is not well defined because of the experimental scatter.

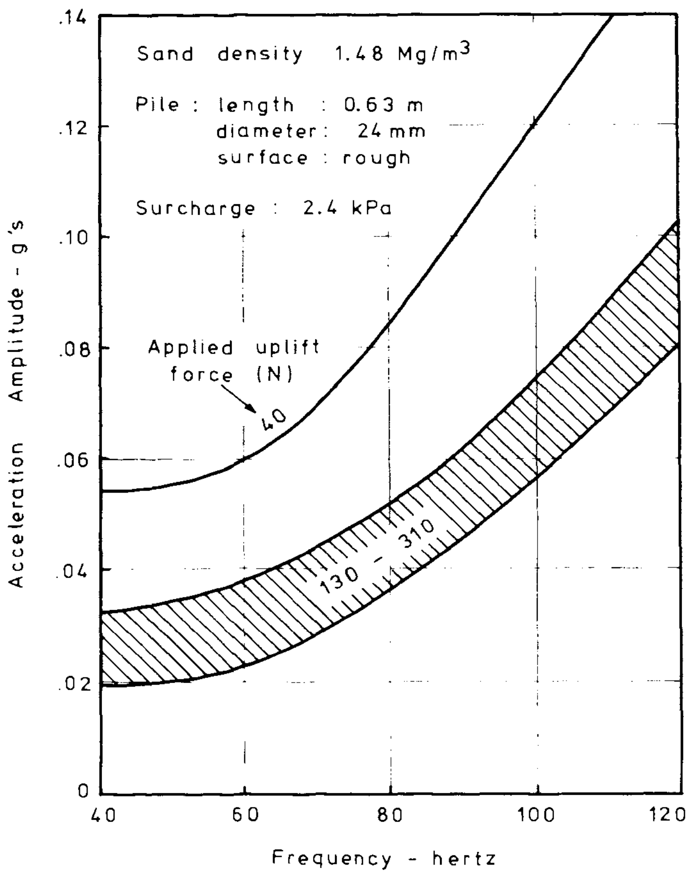

Fig. 5. Observed Amplitudes Causing Uplift Failure

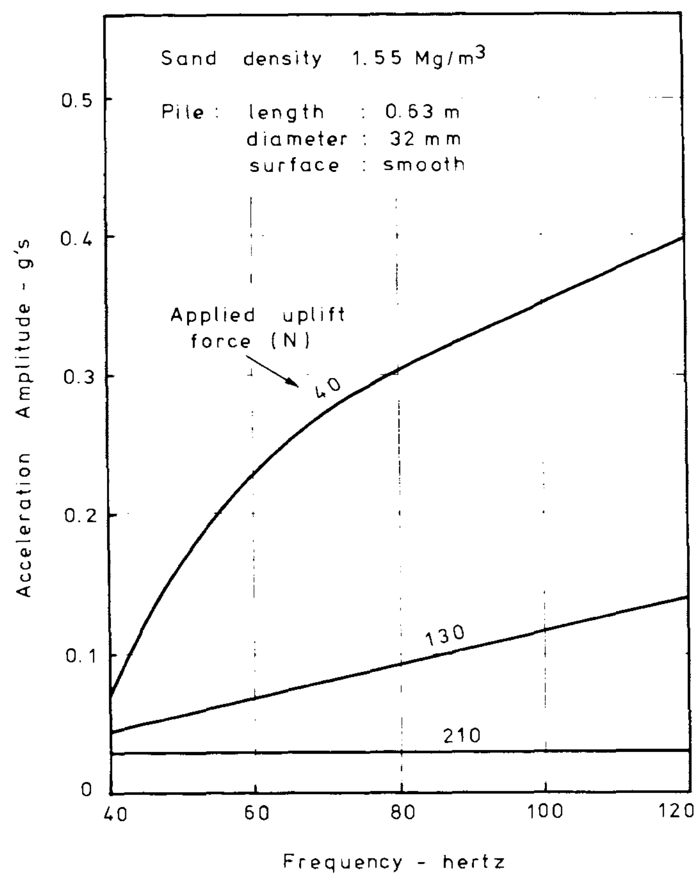

Fig. 6. Observed Amplitudes Causing Uplift Failure

COMPARISONS OF CALCULATED AND OBSERVED BEHAVIOUR

In order to compare the experimentally observed behaviour as set out in Figs. 4, 5, 6 and 7 with the trends indicated by the analytical model as illustrated in Fig. 2, it is necessary to convert the observed acceleration amplitudes into displacement amplitudes. Since the observed vibration was approximately sinusoidal in shape, the displacement amplitude (z_o) can be calculated from the acceleration amplitude ($\ddot{z}_o$ metre/sec^2) by means of the expression

$$z_o = \ddot{z}_o/\omega^2 \qquad (7)$$

The experimental data, of which Fig. 8 is a typical plot, shows that the displacement amplitude required to cause uplift failure of the pile generally decreases as the vibration frequency increases. This trend is consistent with that obtained from theoretical considerations as shown in Fig. 2.

For a more quantitative comparison between calculated and observed behaviour equation (6) has been re-expressed as follows

$$z_o = [T/m\omega_n^2]\ [1 - (F/T)]\ [1 + (2D\omega/\omega_n)^2]^{-\frac{1}{2}} \qquad (8)$$

For the rough 34 mm diameter pile in the loose sand (1.48 Mg/m^3), the theoretical displacement amplitude (z_o) required to cause pile failure has been plotted against (F/T) in Fig. 9 for values of damping ratio (D) of 0 and 1. The lines plotted demonstrate that the required displacement amplitude is relatively insensitive to damping ratio. Superimposed on this figure are the experimentally observed amplitudes corresponding to pile uplift failure. A number of observations of the natural frequency of the buried pile was made and values between 200 and 400 hertz were obtained. The theoretical lines corresponding to these natural frequencies bracket the experimental points, indicating an approximate measure of agreement between calculated and observed behaviour.

CONCLUSIONS

The displacement amplitude of vibration required to cause pile uplift failure was found experimentally to decrease as the vibration frequency increased. This trend agrees with the predictions from an analytical model based upon the behaviour of a damped mass-spring system. The displacement amplitudes required for pile failure decrease as the magnitude of the statically applied uplift force is increased, the relationship depending mainly upon the natural frequency of the pile-soil system.

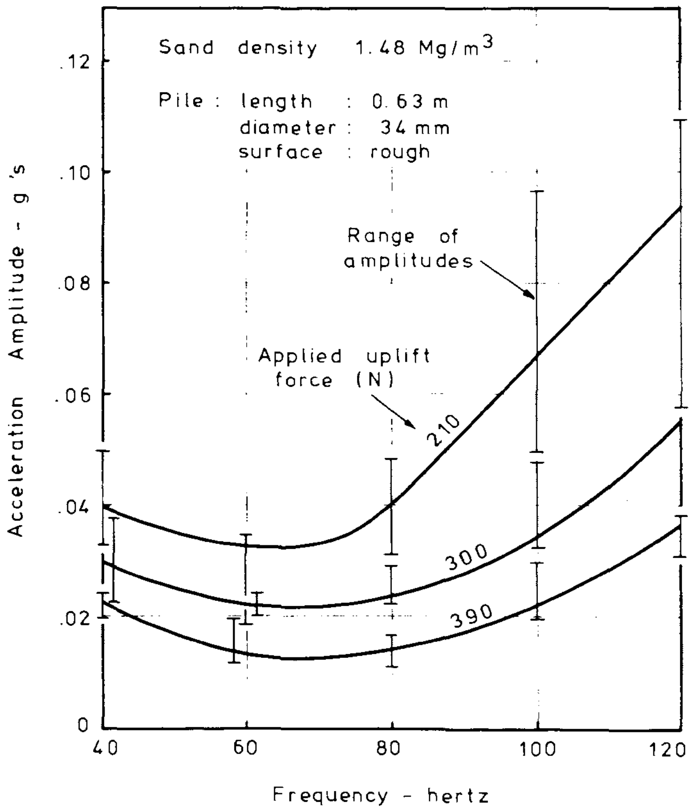

Fig. 7. Observed Amplitudes Causing Uplift Failure

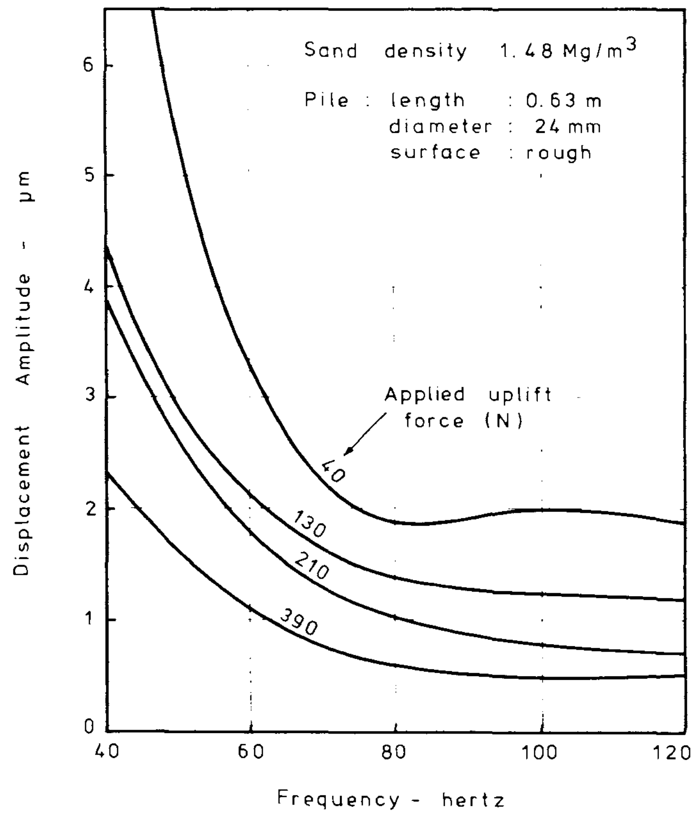

Fig. 8. Displacement Amplitudes Causing Uplift Failure

Quantitative comparisons between calculated and observed displacement amplitudes yielded approximate agreement.

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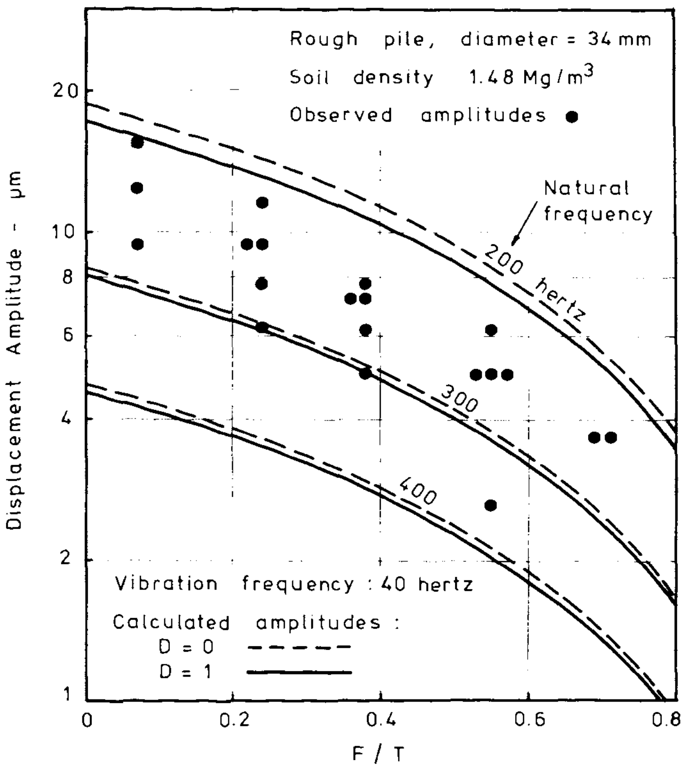

Fig. 9. Observed and Calculated Failure Amplitudes