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Parametric Study of Horizontal Permanent Displacement on Sand

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Australia

SYNOPSIS: Dynamic loading such as cyclic loading should be taken into account in designing shallow foundations for any dynamically related structures. Horizontal permanent displacement, which can occur at any time due to wind and/or wave and dynamic loads of moving vehicles, can significantly reduce the bearing capacity of the footing. Effects of dynamic soil properties, e.g. frequency, Poisson's ratio, Young's modulus, on the permanent displacement are considered and the assumption of the linear variation between deformation and cycles can be used to predict the long-term horizontal permanent displacement.

Sensitivity analyses for both pure sliding and coupled rocking and sliding vibrations of a rigid rectangular footing are also carried out with the following variables: internal damping, added soil mass, rocking level, amplitude of cyclic load and initial constant horizontal load.

INTRODUCTION

It appears that relatively little work has been done in evaluating the behaviour of foundations of structures, especially buildings, subjected to highly fluctuating wind loading. The most simple and important aspect that has not been studied is the shallow foundations subjected to horizontally vibrating loads.

To date, most attention has been directed towards evaluating the peak cyclic displacement that occurs during a storm or under vibration rather than the permanent displacement which is an important consideration for structures under vibration or that must resist cyclic loadings.

In order to identify any deficiencies in current design procedures of foundations, this study investigated the influence of amplitude and frequency of loading on footing behaviour under some combinations of conditions such as footing size, footing shape, footing pressures, embedment, and different vibration modes e.g. sliding, coupled rocking and sliding.

PROPOSED THEORETICAL PREDICTION

If the combination of the horizontal static and dynamic loads has the form $P_oT+P_o\sin wt$, then the slip (or permanent displacement) at the base of the footing during vibration could only occur as the following condition is satisfied:

$$P_oT+P_o\sin wt>\tau A \quad (1)$$

where T = Constant
P_o = Magnitude of cyclic load
P_oT = P_s = Initial static horizontal load
w = Circular frequency
τ = Shear resistance
A = Area of footing.

Equation (1) could be represented as follows:

$$\sin wt>\frac{(\tau A-P_oT)}{P_o} \quad (2)$$

There are two solutions for t in Eq.(2), and the difference of the solutions is the time t_p ($=t_2-t_1$), in which the slip of the footing occurred during the first cycle. The permanent displacement, h_d, after each cycle could be calculated from:

$$h_d=x(t_2)-x(t_1) \quad (3)$$

where x(t) can be obtained by solving nonhomogeneous linear equations from the analytical treatment of the coupled rocking and sliding vibrations (Richart et al, 1970 or the accompanying paper (Truong, 1991).)

The total horizontal permanent displacement, H or x(t), depends on the failure ratio R_f, which is the ratio of the maximum shear stress and the ultimate shear stress, provided that the shear stress/displacement relationship is nonlinear using the hyperbolic model (Clough and Duncan, 1969). It can be expressed by a power function (Daniel and Wood, 1971) as follows:

$$X(t)=H=h_dN^{k1}=At^{k2} \quad (4)$$

where N= Number of cycles
k1 and k2 = Constants depend on the failure ratio R_f.

If k1 = 1, then

$$X(t)=h_dN \quad (5)$$

LUMPED PARAMETERS

Values of stiffness and damping of different modes of vibrations have been used in the analysis based on Richart et al. (1970) and Truong (1991). The new values of stiffness developed in the companion paper by Truong (1991) are linearly proportional to the circular frequency of the horizontal cyclic load of the form $P_oT + P_o sinwt$; those for damping are inversely proportional to this frequency.

EQUIPMENT AND EXPERIMENTAL LAYOUT

To study the behaviour of shallow foundations of structures subjected to highly fluctuating wind loading or any cyclic loading, it was decided to carry out tests on small-size timber footings in a laboratory-controlled situation. The footings were located initially on the surface of a sand mass and the effect of a small degree of embedment of the footing in the sand examined. The wind load was simulated by using a servo-controlled hydraulic system to apply static and cyclic loads varying in intensity and frequency. The applied loads were recorded by using a load cell; the horizontal and vertical displacements were recorded by using a Linear Variable Differential Transformer (LVDT) and two potentiometer-type transducers, respectively. The load cell, LVDT and the two transducers were connected to a four channel Watanabe heat pen recorder (Fig.1).

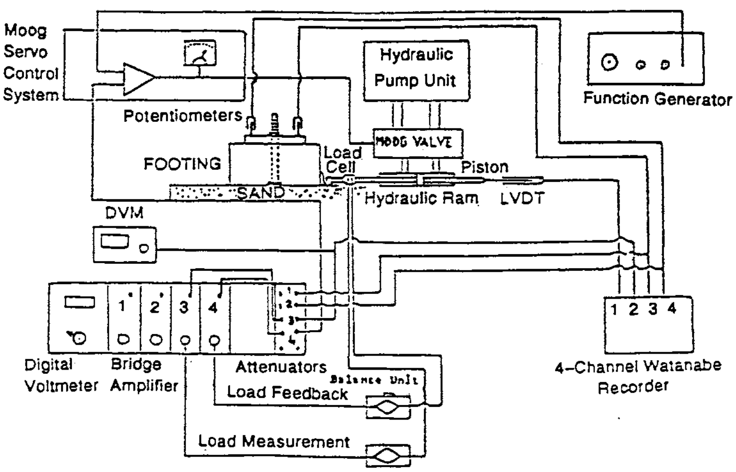

Fig.1 Schematic Diagram of the Apparatus

The footings were placed on a large pit of dry sand which was prepared by pluvial deposition (Kolbuszewski, 1948). Some relevant soil properties are:

Dry Density ....1510 Kg/m^3
Max. Dry Density...... 1675 Kg/m^3
Min. Dry Density...... 1465 Kg/m^3
(According to SAA AS1289 E5.1)

Specific Gravity........2.65
Mean Grain Size.........1.2 mm
Uniformity Coefficient..1.87

EXPERIMENTAL RESULTS

The results obtained from the dynamic tests are compared with the results of direct shear tests and static friction tests.

Twelve direct shear tests were conducted: six of them were carried out in which the shearing was continuously advanced until the maximum allowable movement was reached; the remaining six tests were subjected to the backward-forward movement condition. Area corrections on shear stress were made. The value of internal friction angle at the shearing rate of 0.02367 mm/min. was found to be about 7 degrees lower than the value at the shearing rate of 2.958 mm/min., which was 49 degrees. The higher the shearing rate, the higher the angle of shearing resistance that could be expected. The value of internal shearing resistance of the sand at the shearing rate of 2.958 mm/min. and 0.592 mm/min. under forward-backward motion was the same, i.e. 47 degrees.

For static friction tests, the residual or minimum static force was taken as the minimum horizontal load at a large horizontal displacement or the load close to 40 mm maximum displacement of the hydraulic ram. The friction ratios were taken as the ratios of maximum to minimum static forces. The maximum friction angle was 44 degrees for the rectangular footing R10 which had the friction ratio of 1.16.

DISCUSSION OF RESULTS

In general, the permanent displacement could only occur when the combination of the constant load P_s and the amplitude of cyclic load P_c exceeded the value of the maximum static horizontal load irrespective of the value of the constant load or the amplitude of the cyclic load (Fig.2). The permanent displacement increases with the increase of the amplitude of cyclic load provided that the same constant load and the number of cycles or time were used. The higher the value of the constant load, the bigger the permanent displacement, under the same amplitude of cyclic load and frequency.

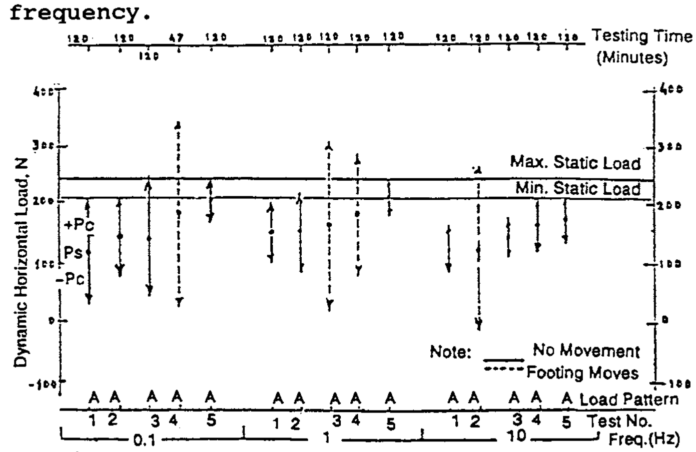

Fig.2 Permanent Displacement of Rectangular Footing R10 Under Various Frequencies and Load Conditions

For the pure sliding condition, the increase of frequency increases horizontal permanent displacement, which also increases with the increase of Poisson's ratio (Fig.3).

The bigger the area of the footing, the higher the friction between the footing and the sand, with the condition that the permanent displacement could only take place when the combination of the initial constant load and the amplitude of the cyclic load exceeds the static horizontal load. So the bigger the area of the footing, the higher the safety factor that could be expected, provided the same design load was used.

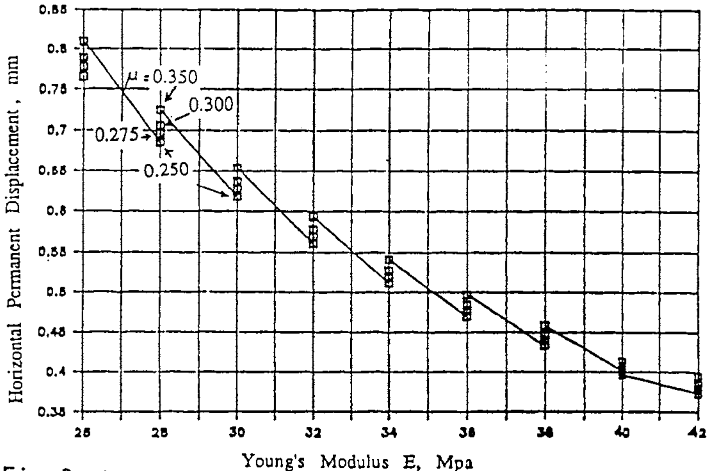

Fig.3 Horizontal Permanent Displacement With Young's Modulus

The higher the normal pressure of the footing, the higher the value of the base friction; this result was also found by Drumm et al. (1984). Thus a higher combination of the constant load and the amplitude of the cyclic load is required to cause permanent displacement.

Finally, the experimental results reveal the same trends as the results obtained from the proposed theory, e.g. (i) the same conditions for permanent displacement (Eq.1). and (ii) the same equation for permanent displacement-time curves (Eq.4).

The increase of the rocking level of the horizontal load increases the rocking angles and horizontal permanent displacement, and decreases the vertical permanent displacement.

The increase of the shear modulus will always decrease the horizontal and vertical permanent displacements and rocking angles. The decreasing rate of horizontal permanent displacement is the same and independent of the rocking level.

An increase in Poisson's ratio tends to insignificantly increase the horizontal and vertical permanent displacements, but slightly decrease the rocking angles.

The prediction of the horizontal permanent displacement using the new values of stiffnesses and dampings in the accompanying paper (Truong, 1991) agrees very well with the experimental data, even assuming a linear relationship between the horizontal permanent displacement and the number of cycles (Fig.4 and Eq.5). The old stiffnesses for different modes of vibrations (Richart et al., 1970) tend to underestimate the horizontal permanent displacement. The reason is that the different dynamic loads have different dynamic stiffnesses (Truong, 1991).

The lower the centre of gravity of the footing system or the higher the values of internal damping, the lower the values of horizontal and vertical permanent displacements and rocking angles.

The horizontal permanent displacement behaviour changes with the variations in the magnitude of

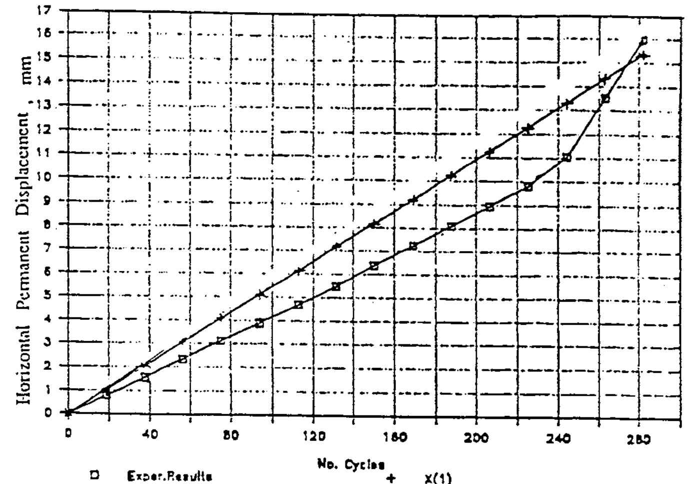

Fig.4 Horizontal Permanent Displacement With New Lumped Parameters - Footing R10 (0.1 Hz)

applied loads. Three different modes of behaviour corresponding to varying composite loads could be identified from the permanent displacement-time curves obtained as (i) shake-down permanent displacement (Mode 1), (ii) linear relationship (Mode 2) and (iii) larger final permanent displacement rate (Mode 3) (Fig.5).

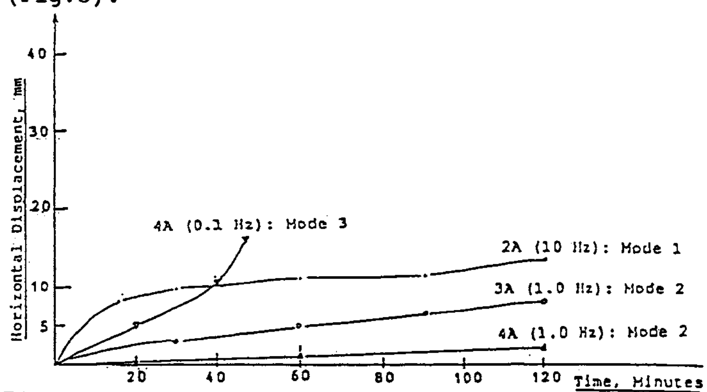

Fig.5 Permanent Displacement Rate Under Different Loading Conditions of Rectangular Footing R10.

An attempt was made to indicate graphically the different type of behaviour according to the initial constant load and cyclic amplitude with a view to comparing the results obtained for different footings and also to extend these results to other footing sizes. The initial constant load and the cyclic load amplitude were normalized by dividing them with the maximum static load (at failure) for the same footing (Fig.6). The plot shows three different modes of behaviour of rectangular footing, even though the points are not numerous enough to mark clear boundaries as described above.

CONCLUSIONS

The horizontal permanent displacement always increases with increase in the frequency of the cyclic load and decreases with increase in Young's modulus. The change of the value of Poisson's ratio from 0.25 to 0.35 for sand tends to slightly increase the horizontal permanent displacement.

The calculated horizontal permanent displacements using the old values of stiffness

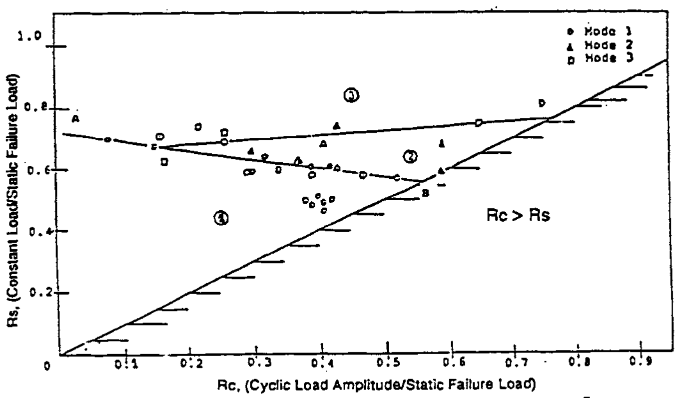

Fig.6 Variation in Permanent Displacement Behaviour With Static and Cylic Loads For Rectangular Footing on Surface of Sand Deposits

and damping (Richart et al., 1970) are very small compared to the actual values from the experimental results.

The new values of stiffness and damping should be used to calculate the horizontal permanent displacement if the force of P_0sinwt was applied. The lower the centre of gravity of the footing system or the higher the values of internal damping, the lower the values of horizontal and vertical permanent displacements and rocking angles. The effect of added soil mass on the horizontal permanent displacement is negligible.

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