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CYCLIC LATERAL LOADING OF PILES IN SOFT CLAY

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SYNOPSIS

A series of model pile tests was carried out to study the pile response to cyclic lateral loads in soft clay. The piles were instrumented with strain gauges so that bending moments developed along the pile could be determined. In addition, the pile head lateral displacement and rotation were simultaneously recorded. The results obtained from the cyclic lateral pile tests were compared to numerically predicted pile response. The numerical analysis treated the pile as an elastic beam on non-linear springs whose characteristics were developed on the basis of the test results and depended on the number of stress cycles. The measured and predicted pile responses were also compared to predictions made using soil reaction criteria proposed by others, which proved to be less satisfactory.

INTRODUCTION

The prediction of the response of piles subjected to cyclic lateral loading is one of the main problems encountered in the analysis and design of pile foundations. Because of the high non-linearity of the stress-strain soil behavior, the lateral pile response is also non-linear even for low levels of the applied load. This has been proved experimentally by several investigators (Matlock, 1970; Reese et al, 1975; Reese and Welch, 1975; Georgiadis and Butterfield, 1982; Abendroth and Greimann, 1990) and resulted in the development of non-linear methods of analysis. The approach most commonly adopted for the analysis of laterally loaded piles is the well-known "p-y" method which is based upon a modified Winkler spring hypothesis. It utilizes non-linear soil springs whose characteristics (p-y curves) depend on the soil properties, the depth below ground surface, the pile diameter and the type of loading (static or cyclic). Criteria for determining "p-y" curves have been proposed by several researchers (Matlock, 1970; Reese et al, 1974; Sullivan et al, 1979) for different types of soil and have been included in several codes of practive (e.g. API, 1984).

The experimental results reported in this paper were obtained through a series of model pile tests involving cyclic lateral loading. The pile response below ground level can be monitored either with electrical resistance strain gauges bonded along

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the pile or with tilt indicators (Price et al, 1987). The former of these approaches provides more accurate determination of the soil reaction and therefore it was adopted in the model tests of the present study. The aim of these tests was to throw some more light to the development of "p-y" criteria for cyclic loading. The test results were compared to numerical predictions made using different "p-y" criteria and finally a new relationship describing the soil response for cyclic lateral loading of piles in soft clay was developed, which proved to provide very satisfactory results.

MODEL TESTS

Six lateral load tests were performed on 500 mm long aluminium closed ended piles of 19 mm outside diameter and 1.5 mm wall thickness. Their flexural stiffness, EI, was 0.2 kN.m^2. All the piles were installed in a soft medium plasticity clay bed (700 mm wide by 1000 mm long by 800 mm deep) in which $W_L = 42\%$, $W_P = 24\%$, $W = 26\%$ and $c_U = 28$ kN/m^2 (measured in unconfined compression and vane tests).

The horizontal load was applied to the pile head at ground elevation through a loading system comprising a 25 mm ID steel ring with knife edged inner perimeter, attached to a steel wire which was loaded through a sprocket with dead weights (Fig. 1). The effective lateral loads applied by this system to the pile head were 38, 92, 146 and 202 Newtons and were cycled ten times each.

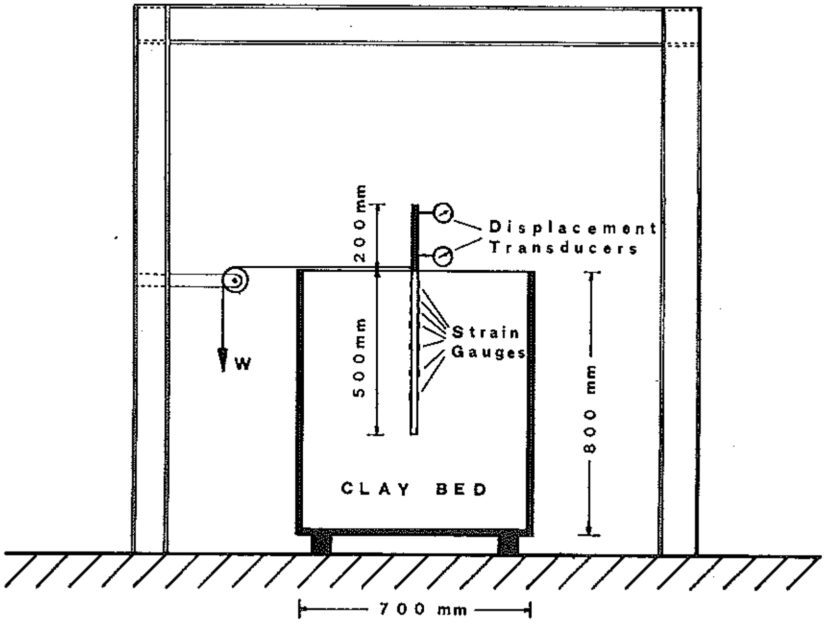

Fig. 1 Experimental apparatus.

The upstanding pile lengths were stiffened by a 10 mm × 10 mm steel bar so that by simultaneous measurement of the horizontal displacement of two points along them, the lateral displacement and rotation of the pile at ground level could be determined. In addition, each pile was instrumented with seven pairs of strain gauges positioned along its length so that the distribution of bending moments could be measured during the tests. The strain gauge spacing was based on a preliminary numerical analysis which provided the variation of bending moments with depth. They were placed at depths of 40, 80, 120, 160, 230, 310 and 380 mm below ground level. Each pair of strain gauges was glued in small flat grooves made on opposite sides of the pile (in the plane of loading) and were protected by a hard epoxy coating. The gauge wires passed through small holes made in the pile wall and were located into the interior of the piles. All piles were calibrated before testing to provide accurate determinations of the bending moments. The measurements taken during the tests were recorded by a multi-channel data logger.

TEST RESULTS

Fig. 2 presents the load vs. horizontal displacement and load vs. rotation relationships of the pile head measured during the six pile tests for the first loading cycle ($N = 1$). Similar relationships demonstrating the non-linearity of the pile response even for low load levels, were also obtained for the other loading cycles. The mean load vs. displacement and load vs. rotation relationships for $N = 1, 2, 5$ and 10 are shown in Fig. 3, illustrating the significant effect of cycling on the measured pile head lateral displacement and rotation.

The bending moments along the pile length induced by the first application ($N = 1$) of lateral loads of 38, 92, 146 and 202 Newtons are presented in Fig. 4. An important feature of this figure is that the depth at which the bending moment reaches its maximum value increases with increasing pile head load (H) from 80 mm for $H = 38$ Newtons to 140 mm for $H = 202$ Newtons. This is also a result of soil non-linearity which in conjuction with the non-linear load vs. displacement response of the pile head suggests that the use of a linearly-elastic method of pile analysis may lead to erroneous results.

The effect of load cycling on bending moments is shown in Fig. 5 which presents typical average (from the six tests) bending moments versus depth relationships for $N = 1, 2, 5$ and 10 induced by a 146 Newtons lateral load. It is noted that the maximum bending moment measured at $N = 10$ is about 20 percent higher than the one measured during the first cycle.

INTERPRETATION OF TEST RESULTS

The average load vs. pile head displacement (H-y_0), load vs. pile head rotation (H-$\tan\theta_0$) and bending moment vs. depth (M-z) relationships in the previous section were utilized to determine the shear force (Q), the soil reaction (p), the lateral

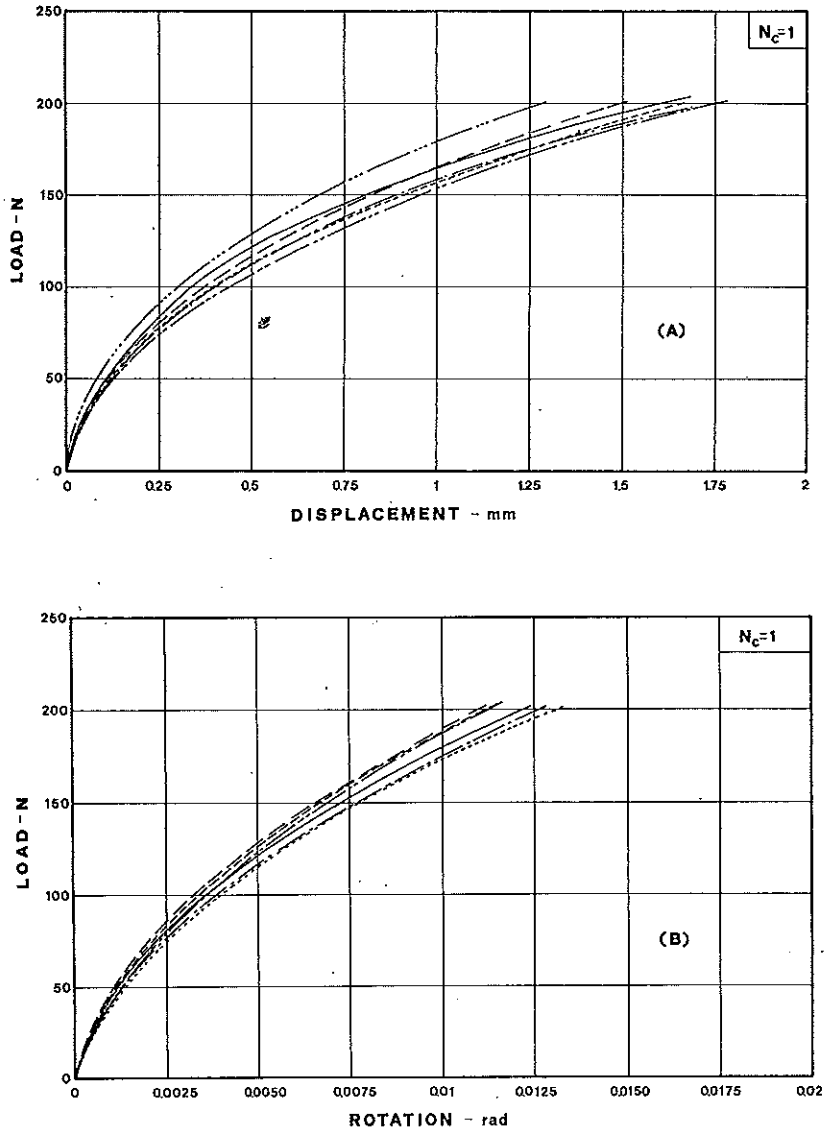

Fig. 2 Experimental load vs displacement (α) and load vs rotation (b) relationships for N = 1.

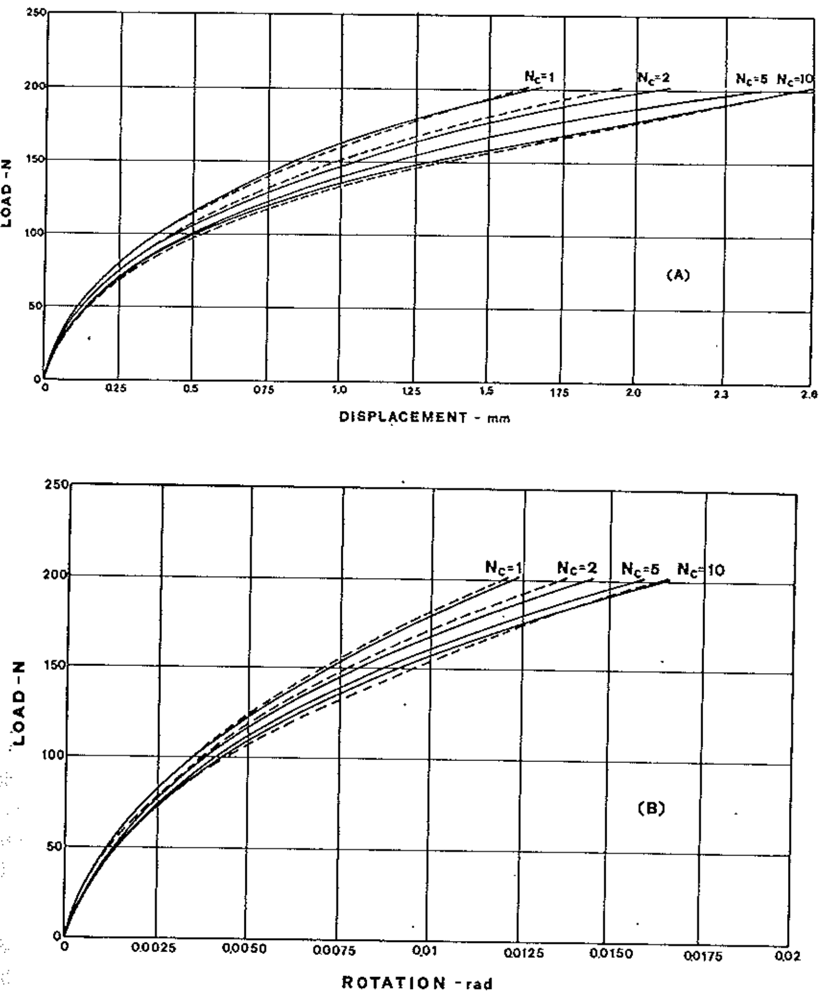

Fig. 3 Mean experimental load vs displacement (a) and load vs rotation (b) relationships for N = 1 , 2, 5, 10.

displacement (y) and the rotation (tanθ) along the pile length for any value of the applied lateral load H. To obtain the variation of shear force and soil reaction with depth (Q-z and p-z diagrams), the M-z diagrams of Fig. 5 were differentiated once and twice, respectively :

$$Q = dM / dz \tag{1}$$

$$p = d^2M / dz^2 \tag{2}$$

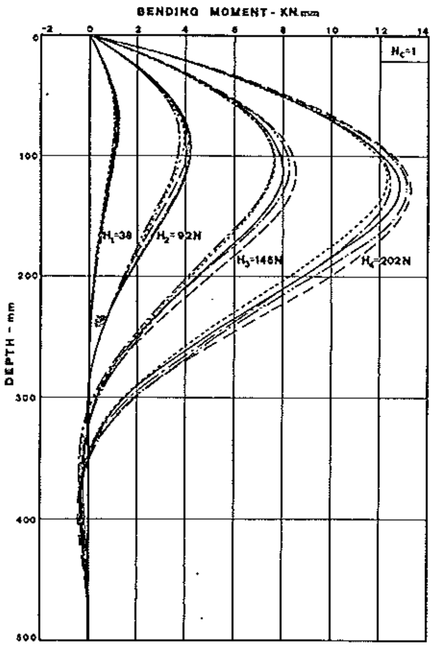

Fig. 4 Experimental bending moment diagrams for N = 1.

This was performed using a simple cubic spline function which interpolates between two successive pairs of experimental points (M_i, Z_i) and (M_{i+1}, Z_{i+1}), instead of using a higher order polynomial for the full set of experimental points, which was found to result in significant errors on the second derivative (soil reaction).

To obtain the variation of $\tan\theta$ and y with depth, the M-z curves of Fig. 5 were integrated once and twice, respectively, using as boundary conditions the pile head displacements (y_0) and rotations ($\tan\theta_0$) presented in Fig. 3 :

$$\tan\theta = \int (M/EI)\,dz \qquad (3)$$

$$y = \iint (M/EI)\,dz \qquad (4)$$

Typical p, Q, $\tan\theta$ and y versus depth (z) diagrams determined with this procedure for N = 1 and H = 202 Newtons are presented in Fig. 6. Subsequently, these diagrams were used to establish the soil reaction versus lateral pile displacement relationships (p-y curves) at several depths below ground elevation. Points defining "p-y" curves for N = 1 and N = 10 at depths of 0, 40, 80 and 120 mm are presented in Figs. 7 and 8, respectively.

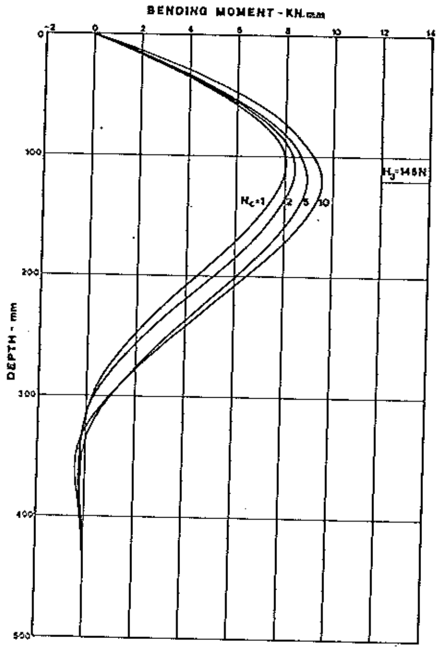

Fig. 5 Mean experimental bending moment diagrams for H = 146 Newtons and N = 1, 2, 5, 10.

ANALYSIS

In order to predict the pile response to cyclic lateral loads, a computer program was developed in which the pile is considered as an elastic beam on non-linear soil springs, analyzed with the Transfer Matrix Method (Pestel and Leckie, 1963). To determine appropriate load-displacement relationships for the non-linear springs (p-y curves) for N = 1, the following hyperbolic function which is widely used in stress-strain soil problems (Kondner, 1963), was considered and found to fit remarkably well to the data points presented in Fig. 7 :

$$p = y / [(1/k) + (y/p_u)] \qquad (5)$$

where k is the initial stiffness of the p-y curve and P_u is the ultimate soil resistance.

The value of p_u per unit pile length may be expressed as (Matlock, 1970) :

$$p_u = N_p c_u D \qquad (6)$$

where c_u is the undrained shear strength of the soft clay, D is the pile diameter and

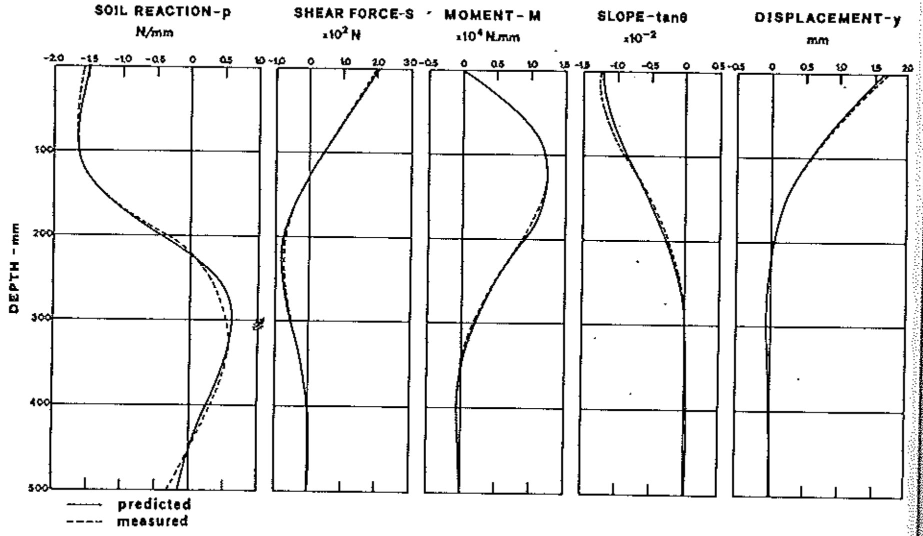

Fig. 6 Typical measured and predicted pile responses for N = 1 and H = 202 Newtons.

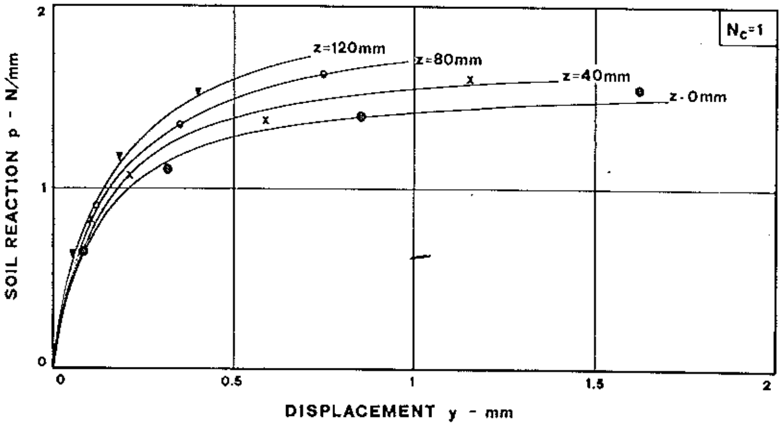

Fig. 7 "p-y" curves for static loading (N = 1).

N_p is a non-dimensional coefficient which increases with depth, z, from 3 at ground level to 9, according to the equation :

$$N_p = 3 + (\gamma z/c_u) + J\,(z/D) \qquad (7)$$

where γ is the unit weight of the soil and J is an empirical coefficient. Two pile tests reported by Matlock (1970) indicated J values of 0.5 and 0.25 while a value of 0.14 was found to be more appropriate for the present study of piles in soft clay.

The parameter k in Equation 5 (the initial stiffness of the p-y curve) is a function of the basic elastic soil properties (elastic modulus and Poisson's ratio) and the pile diameter and flexural stiffness (Vesic, 1961).

It was found that Equation 5 approximates the experimental results much better than the empirical curve proposed by Matlock (1970). The main reason for this is the different initial stiffness of the two p-y curves, which in Equation 5 corresponds to elastic soil response (dp/dy = k for y = 0) while in Matlock's curve the initial stiffness is infinite (dp/dy = ∞ for y = 0). This infinite initial stiffness results in an erroneous pile response at the lower part of the pile where the soil resistance and the displacements are small.

Equation 5 was modified to take into account the number of loading cycles, N, and the applied stress level expressed as the ratio of cyclic soil resistance to ultimate soil resistance, p/p_u. A comparison of Figs. 7 and 8 reveals that the displacements increase with increasing number of cycles and that the effect of cycling is more pronounced at large stress levels (p/p_u). A modified version of Equation 5 which fulfills these two features of cyclic behavior was found to be the following :

$$y / p = [1 + 5(p/p_u)^4 \log N] \,/\, k[1-(p/p_u)] \qquad (8)$$

which for N = 1 becomes identical to Equation 5. The initial stiffness of this relationship (dp/dy for y = 0) is equal to k and therefore independent of number of cycles. This implies that cycling does not affect the pile-soil response at low stress levels, a feature which is very well established in cyclic soil behavior.

Fig. 8 illustrates that the "p-y" curves determined with Equation 8 for N = 10 are in very good agreement with the experimentally determined "p-y" points. Similarly good is the agreement shown in Fig. 7 between experimental points and Equation 8, for N = 1.

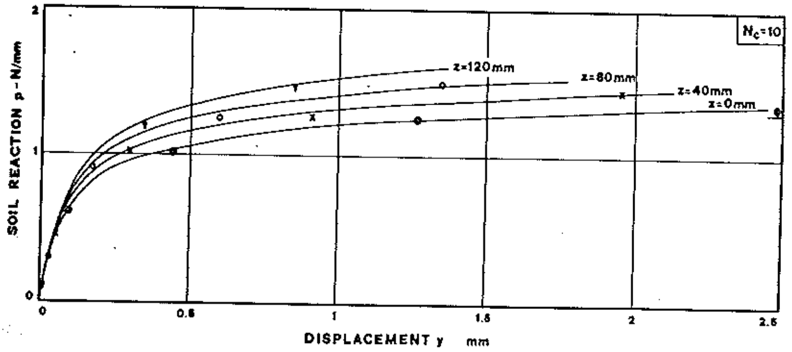

Fig. 8 "p-y" curves for N = 10.

Equation 8 together with an iterative procedure enabled the non-linear soil response to be satisfactorily modeled along the pile for any number of loading cycles. This soil model was introduced into the Transfer Matrix Analysis and provided the non-linear pile response to cyclic lateral loads.

COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

A typical comparison between measured and predicted pile responses is presented in Fig. 6. It shows the variation of soil resistance, shear force, bending moment, rotation and lateral displacement along the pile length for the first application (N = 1) of a lateral load of 202 Newtons. The remarkably good agreement between measurements and predictions shown in this figure was also observed for any other combination of lateral loads and number of loading cycles.

Figs. 9 and 10 compare predicted to mean measured lateral load (H) versus pile head displacement (y_0) relationships for N = 1 and N = 10, respectively. Plotted on the same figures are also two load-displacement relationships determined using the "p-y" criteria of Matlock (1970) and Reese and Welch (1975). It is noted that the measured pile head response and the response predicted using the "p-y" criteria proposed in this paper are almost identical for both N = 1 and N = 10. On the other hand, the predictions made with the other "p-y" criteria are quite good for static loading while for the tenth load cycle the predictions underestimate the pile head displacements by more than 50 percent.

Similar are the comparisons regarding the bending moments which are presented in Figs. 11 and 12 for N = 1 and N = 10, respectively. Measurements and predictions made with the "p-y" criteria of this paper are about identical for both

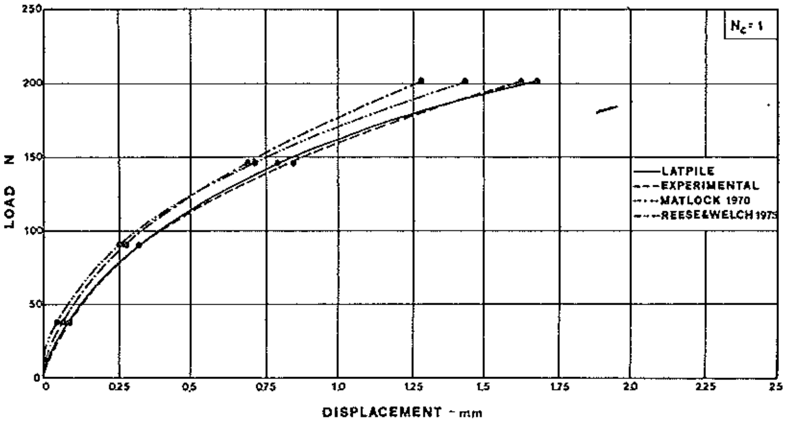

Fig. 9 **Predicted and experimental load vs pile head displacement relationships for N = 1.**

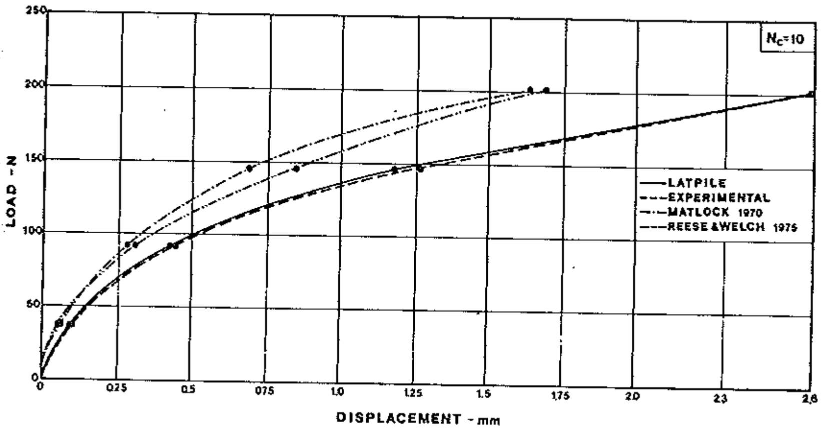

Fig. 10 **Predicted and experimental load vs pile head displacement relationships for N = 10.**

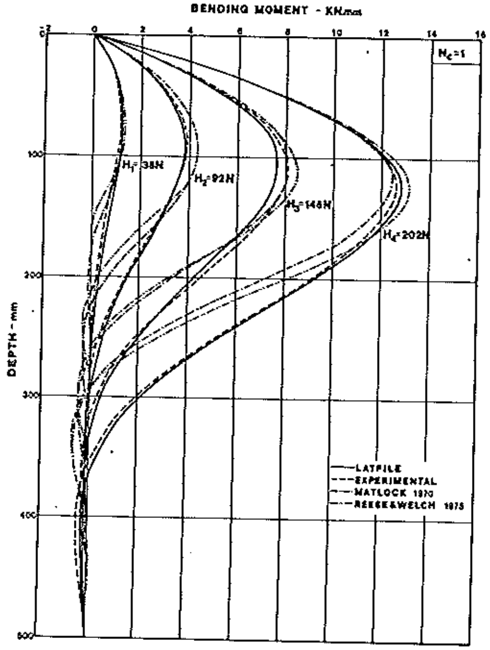

Fig. 11 **Predicted and experimental bending moments for N = 1.**

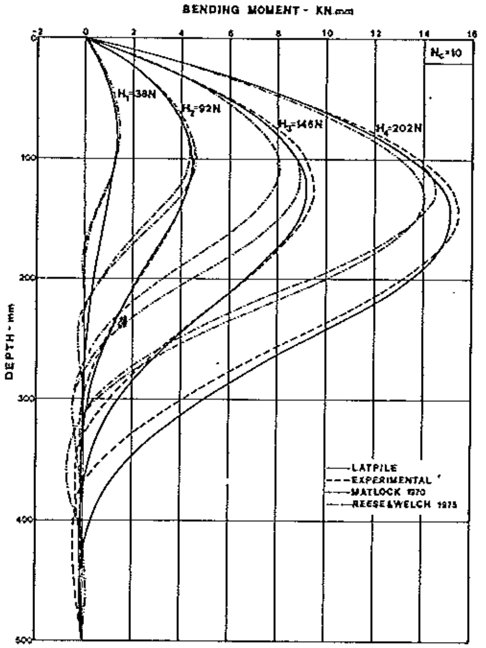

Fig. 12 Predicted and experimental bending moments for N = 10.

static and cyclic loading. The difference between measured bending moments and those predicted with the Matlock (1970) and Reese and Welch (1975) "p-y" criteria is less than the difference in pile head displacements, on the order of 10 percent, but the difference becomes very large at depths below the point where the maximum bending moment occurs. This is caused by the fact that these criteria assume infinite initial slope of the "p-y" curve and therefore overestimate seriously the soil stiffness at large depths (below six pile diameters) where the displacements are small. It is noted that this discrepancy is larger for cyclic loading than for static. For example, at a depth of 12 pile diameters the predictions underestimate the measured bending moments by about 55 percent for N = 1 and by about 70 percent for N = 10.

CONCLUDING REMARKS

For piles subjected to cyclic lateral loads it is customary to utilize an analysis which caters for the depth-variable non-linear soil characteristics. The main problem in this type of analysis is to determine reliable soil resistance vs. lateral displacement relationships ("p-y" curves) which must take into account the number of load applications.

In order to develop such curves for piles in soft clay and to evaluate existing relationships, an experimental program was undertaken in which piles instrumented with strain gauges along their length were loaded with cyclic lateral loads. Based on the measured pile response which included the lateral displacements and rotations of the pile head and the bending moments at several points along the pile, a soil resistance vs. lateral displacement relationship was developed which considers apart from the conventional soil properties the cyclic stress level and the number of stress cycles.

This relationship was incorporated into a numerical analysis which predicts the lateral pile response (bending moments, shear forces and displacements along the pile), treating it as an elastic beam on non-linear springs, and proved to provide very satisfactory results. The analysis was also performed using other soil reaction vs. displacement relationships obtained from the literature, which however were found to be less accurate.

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