Behaviour of Steel Piles Under Lateral Load and Moment

by

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SUMMARY. Frequently pile groups must resist lateral loads as well as normal gravity loads. Although battered piles are efficient in resisting lateral forces they are expensive to install so that where conditions are suitable it can be economic to use only vertical piles. The lateral loads are then resisted by flexure within the piles and also by resistance to displacement in the surrounding soil.

This paper contains the results of tests on two fully embedded hollow steel piles that had been instrumented with electric resistance strain gauges. Both end moment and lateral loads were applied to these piles, head displacement head rotation and the distribution of bending strains along the pile being measured. The load deflection behaviour was non-linear with significant time dependent deflections. This creep behaviour increased with increasing load.

The pile soil behaviour has been analysed in terms of an equivalent Winkler medium and the non-linear behaviour accounted for by a reduction in the stiffness modulus. Reasonable agreement was obtained between the measured bending moments and deflected shape and that predicted by an iterative non-linear analysis.

1 INTRODUCTION

In many piled foundations the individual piles are subjected to end shear forces and moments as well as their axial load. If these additional forces are significant, pile deflections may be induced which are large enough to develop inelastic behaviour in the soil. In lateral load tests on piles it has been observed (Feagin (Ref. 1), McClelland and Focht (Ref. 2)) that the load deflection response is non-linear. Nevertheless most methods of pile analysis assume that the soil behaviour is elastic, and that the axial load component is unimportant.

The validity of these assumptions has been investigated in a series of load tests on full scale flexible steel piles. End moments and lateral loads were applied to two hollow instrumented steel piles and their behaviour has been compared with analyses based on two Winkler type media.

2 ANALYSIS OF PILE-SOIL DEFLECTION BEHAVIOUR

A finite element analysis could be applied to this problem. It has many advantages in representing the varying soil strata and the non-linear behaviour of most soils. However, it does involve large storage capacity for a 3-dimensional problem and in practice the accuracy with which the representative soil parameters can be defined does not warrant such a complex analysis. In most situations field test data will be used to idealize the soil behaviour and a simple method of extrapolating from prototype pile tests is all that is required.

The most frequent assumption for the soil behaviour is that it behaves as an isotropic semi-infinite elastic medium. Spillers and Stohl (Ref.3) used Mindlin's equation for the lateral displacement of a point in an elastic medium due to a force applied at some other point and parallel to the surface. In order to account for soil plasticity near the surface they limited the lateral pressure that could be exerted against the pile and assumed a constant resistance when this value was exceeded at any point along the pile. This method of analysis yielded non-linear load deflection plots similar to those found in load tests.

This method would be satisfactory if the elastic assumptions were valid. Most soils exhibit an increasing strength, density and stiffness with depth below the surface. Mindlin's equations are not applicable and a modified form of the Winkler medium appears appropriate. In such a medium the lateral restraint at any depth is assumed to be solely dependent upon the pile displacement at that depth. The stiffness modulus can be defined as a function of depth. Terzaghi (Ref. 4) has suggested either constant stiffness ($k_x = k$) for an isotropic homogeneous elastic medium such as near the surface of an overconsolidated clay or a stiffness increasing linearly with depth to represent cohesionless deposits, and soft normally consolidated clay soils ($k_x = n_h \cdot x$) where k_x is the Winkler stiffness modulus or modulus of subgrade reaction (N/m^2) at depth x and n_h is the coefficient of subgrade reaction (N/m^3).

The assumption of a uniform Winkler modulus yields an accurate representation of the bending moment distribution and the deflections in a beam resting on the surface of the homogeneous elastic medium, provided that the beam is long enough to behave flexibly. The modulus (k) is related to the beam flexural rigidity (EI), width (B) and the elastic parameters (E_s, ν_s) of the soil. Vesic (Ref. 5) has suggested a useful relationship

$$k = \frac{0.65}{B} \sqrt[12]{\frac{B^4 E_s}{EI}} \cdot \frac{E_s}{1 - \nu_s^2} \qquad (1)$$

Real soils are rarely homogeneous and even for small strains exhibit non-linear behaviour. Matlock & Reese (Ref. 6) have suggested that this non-linear behaviour can be accommodated by assuming or determining a non-linear lateral load-deflection curve for each point on the pile and using an iterative type analysis with a modified Winkler stiffness modulus based upon a secant modulus of this curve at the appropriate displacement.

The advantage of this type of analysis is that the pile and soil behaviour are easily represented in a computer program. The simplicity of the program warrants the idealization of the soil behaviour. The pile behaviour is characterized by its differential equation.

$$EI\ y^{iv} + Py'' + w = 0 \qquad (2)$$

where P is the axial load, EI the flexural rigidity of the pile, and w the lateral load/unit length. w can be expressed in terms of the pile deflection (y) and the modified Winkler stiffness modulus (ks) which is the secant modulus of the assumed or measured load displacement function. This differential equation and the appropriate boundary conditions are expressed in finite difference form and the resulting matrix equation solved for the displacements. The effect of the axial load P can be readily included and the non-linear soil behaviour is accommodated with only a few iterations.

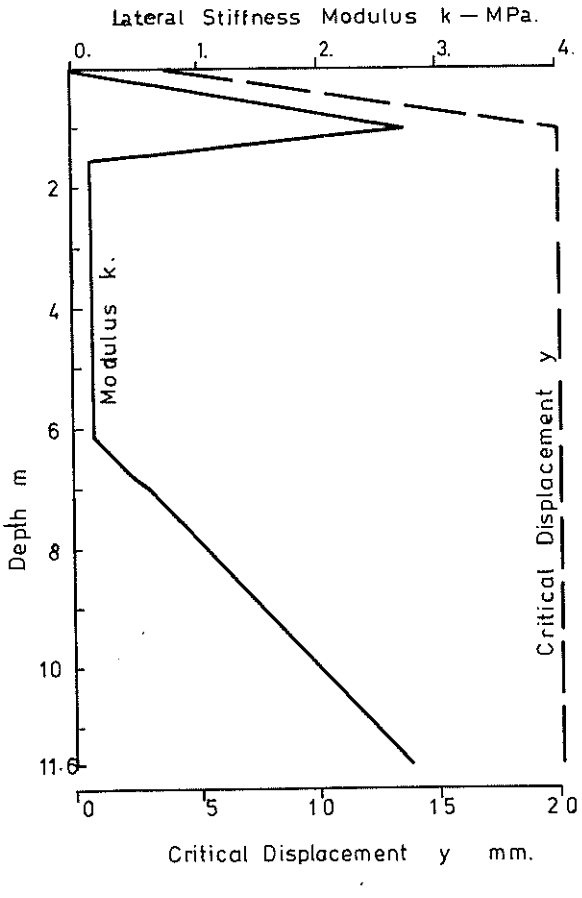

Fig. 1 Assumed Soil Stiffness and Critical Displacement Variations with Depth

A program for an I.B.M. 7044 computer has been developed in which the soil non-linearity is assumed to be of an elastic-plastic type. This is defined by the initial elastic stiffness k and the critical displacement y_{cr} at which the elastic response is equal to the ultimate plastic strength of the soil. Since both the strength and the stiffness increase with depth at about the same rate, this critical displacement does not vary greatly with depth.

Fig. (1) is a representation of the assumed soil properties for the lateral load test on the first pile and Fig. (2) shows the predicted deflections of the pile.

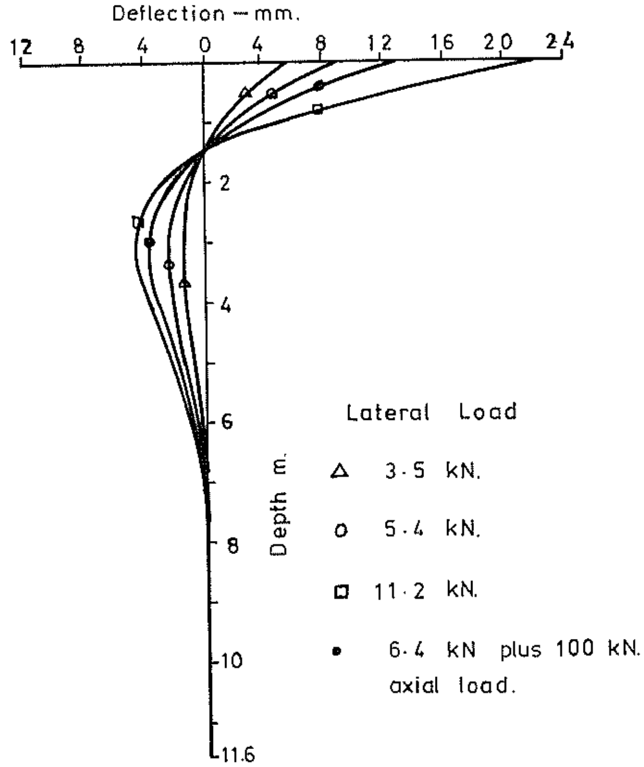

Fig. 2 Predicted Deflections in Pile A - Lateral Load

3 PILE TESTS

During an investigation into the stability of long slender piles two of the instrumented piles were subjected to a series of tests involving end moments and lateral loads. The piles were almost fully embedded with the loads being applied 0.3 m (1 ft) above the ground surface. The soil profile is described in Fig. (3).

It is important to note that although the soft South Melbourne silty clay is critical to the stability of the piles under axial load, it is the surface 1.2 m (4 ft.) depth of ashes and fill which determines the lateral load behaviour of these piles (Davisson and Gill, Ref. 7). The penetrometer tests indicate that this material is appreciably stronger than the underlying silty-clay. Unfortunately, undisturbed samples were not obtained from this material.

Details of the two pile sections used in these tests are shown in Fig. (4). Each pile was instrumented with 150 mm long BL & H type A4 electric resistance strain gauges. These were placed on the inside of both front and back faces of the piles at 600 mm (2 ft.) intervals in the upper 4.27 m (14 ft.) of the pile and at 1.2 m (4 ft) intervals below this depth. A prestressing cable was attached to the toe of the pile and passed up through the hollow centre of the pile. Axial loads at the pile head were applied through a hemispherical bearing. The piles were 11.6 m (38 ft.) long.

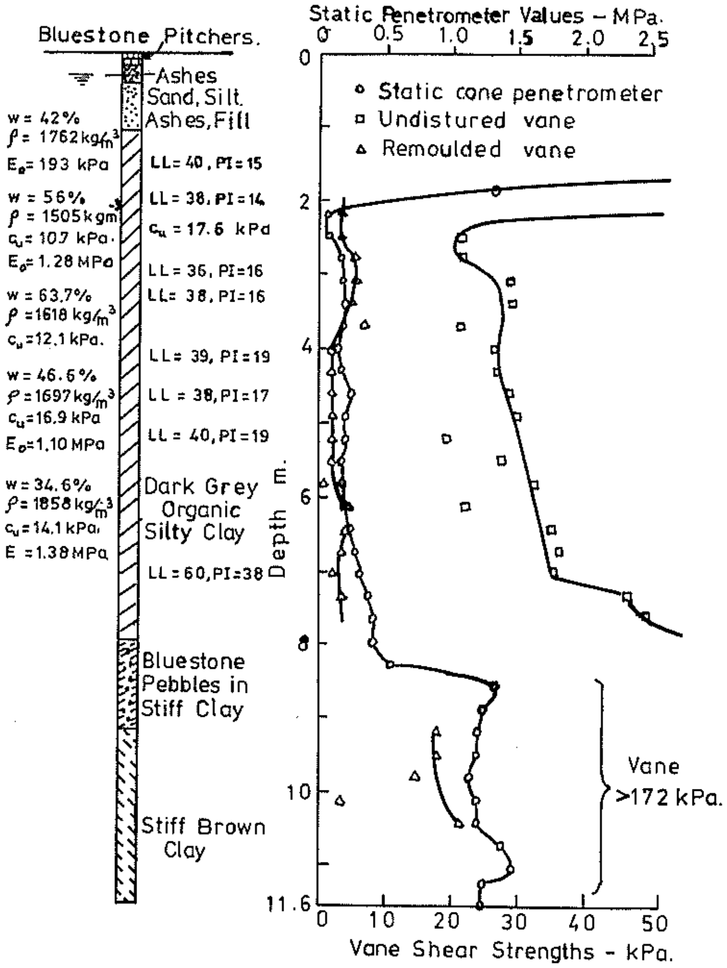

Fig. 3 Borehole and Site Test Results

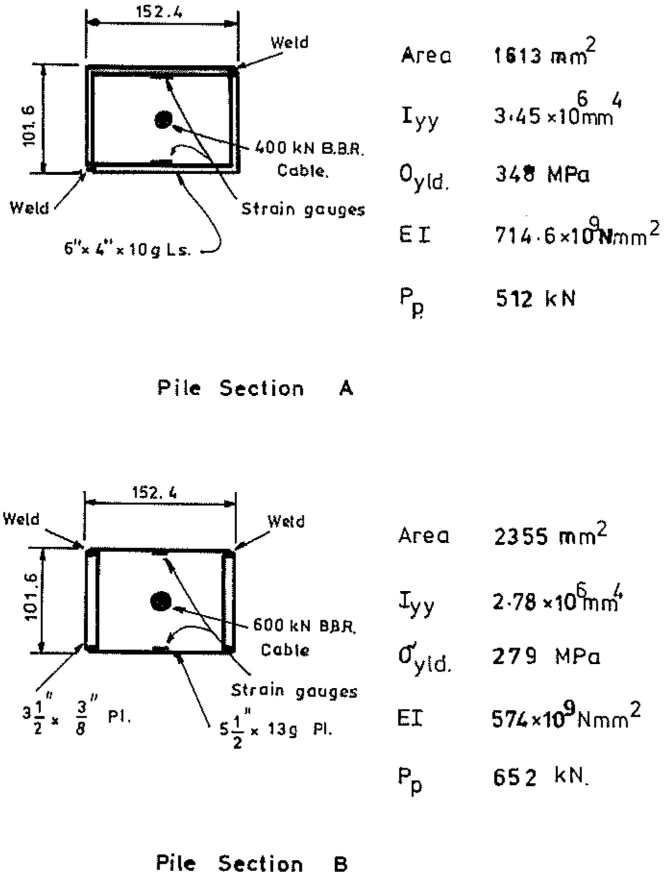

Fig. 4 Test Pile Sections

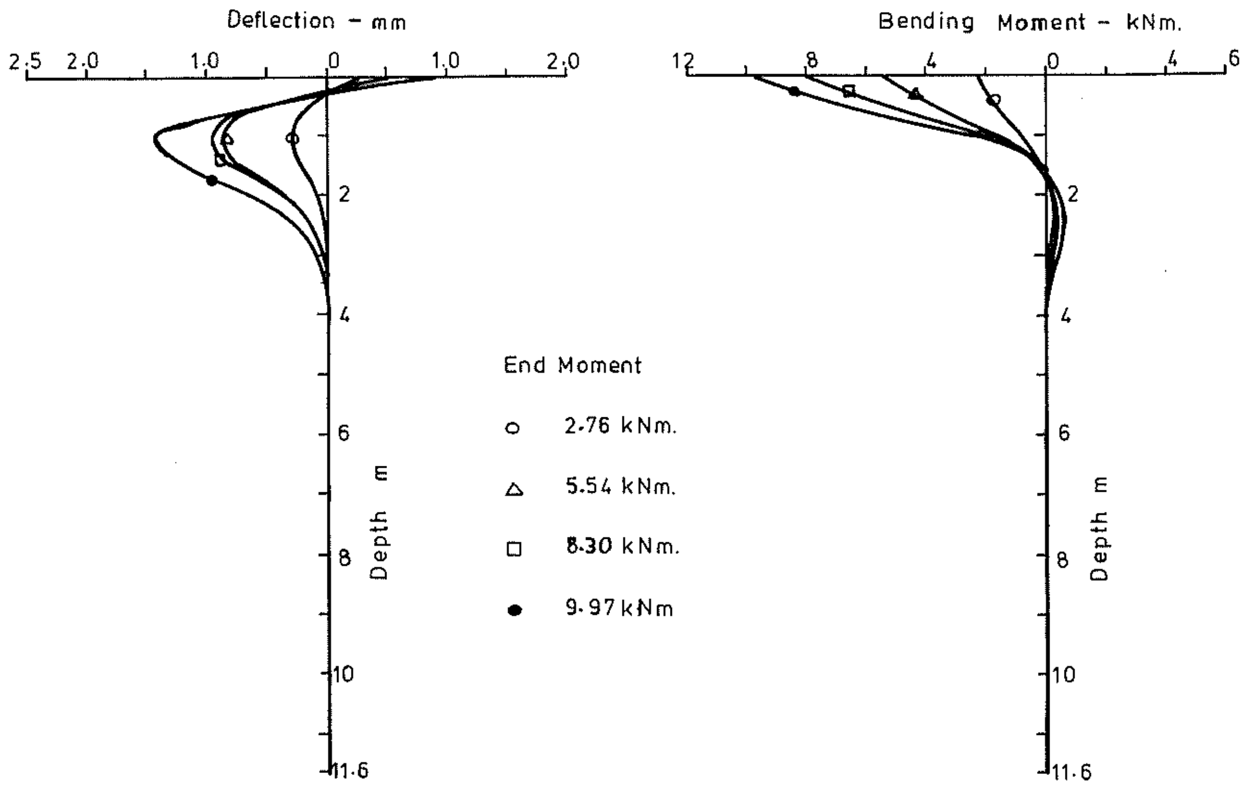

Fig. 5 Deflections and Bending Moments in Pile A - End Moment Loading

4 END MOMENT TESTS

Each pile was loaded with a pure couple. In these tests the pile head was pinned to prevent lateral displacement and head rotations were measured with a precise inclinometer (Bubble sensitivity 2 sec. of arc/division). Fig. (5) shows the typical bending moment distribution and the computed deflected shape of the first pile. In each case the applied end moment has been rapidly diminished to negligible values within the first half wave length.

The bending moment distribution can be differentiated twice to obtain a lateral load function which if divided by the appropriate deflections will give the soil stiffness distribution. This procedure is not very accurate but the average stiffness 'k' over the top half wave length was 4.1 MPa (595 lbf/in^2) for a uniform medium or a coefficient of subgrade reaction n_h of 27.1 MN/m^3 (10 lbf/in^3) for the equivalent linearly increasing stiffness medium.

Other ways of interpreting this data are based on the head rotation - applied moment curve and on the length of the 1st half wave. These values are summarized in Table 1. There is reasonable agreement between these different interpretations and the uniform stiffness Winkler medium gives a more consistent interpretation of this soil behaviour.

5 LATERAL LOAD TESTS

Lateral loads were applied to each pile. In each case large head deflections and bending moments were developed but these were very rapidly diminished with depth. Negligible deflections occurred below 3.6 m (12 ft.) Fig. (6) illustrates the typical deflection and bending moment distribution in the first pile.

The lateral loading system was strain controlled and relaxation in the load occurred. The initial load required to produce a displacement of 27 mm (0.94 in.) in the first pile was reduced by 5.5% after ½ hour, 8% after 20 hours and a maximum of 11% after 72 hours.

The test data has been interpreted in terms of the two idealized soil media and the appropriate soil stiffness parameters are again summarized in Table 1. In this case the head rotation and head sway can be related to the soil stiffness parameter 'k' or n_h. These values are based on the immediate deflection and rotations occurring at the pile head. This behaviour was essentially linear before creep or relaxation affected the values.

$$\text{i.e.} \quad k = 4EI\,(\theta/\Delta)^4$$

$$\text{or} \quad n_h = 7.027\,EI\,\left(\frac{\theta}{\Delta}\right)^5 \qquad (2)$$

These values are significantly less than the values obtained in the end moment tests for this zone of soil. This is consistent with a reduced equivalent Winkler stiffness modulus as the lateral loads produced much greater deflections in the piles. These modulus values are much greater than the values for the soft South Melbourne silts below a depth of 1.5 m (5 ft.) derived from either laboratory tests or from the axial load tests on the piles. This confirms Davisson and Gill's contention that the stiffness of the surface material is critical.

6 COMBINED AXIAL AND LATERAL LOAD

An axial load of 100 kN (10 ton) was applied to the first pile with the prestressing cable attached to the toe of the pile. This is 20% of the short column load capacity of the pile section.

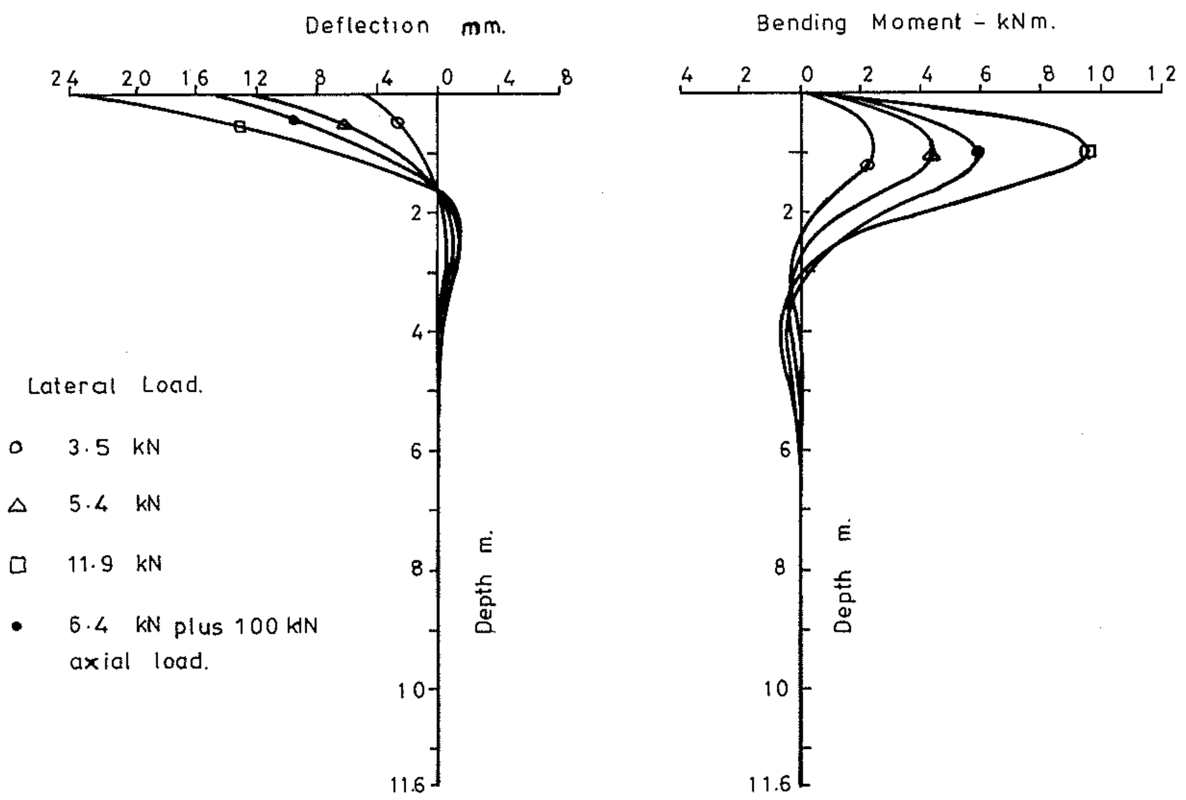

Fig. 6 Deflections and Bending Moments in Pile A - Lateral Loads

TABLE I
SOIL STIFFNESS MODULIE

Type of Test	Method of Evaluating Modulus	Uniform Stiffness k MPa	Linearly Increasing Stiffness n_h MN/m^3	Uniform Stiffness k MPa	Linearly Increasing Stiffness n_h MN/m^3
End	Derived Lateral Loads	4.10	2.71	4.72	3.09
Moment	Head Rotation/Mt	4.14	4.07	3.93	3.99
Test	Depth to Zero Displacement	3.96	1.44	3.10	1.19
Lateral	Derived Lateral Loads	2.28	2.63	2.41	2.80
Load	Head Rotation and				
Test	Translation (θ/Δ)	1.77	2.74	2.00	3.37
	Depth to Zero Displacement	2.07	3.96	1.72	2.77

The lateral displacement of the pile head was limited to 16.5 mm (0.65 in.) to prevent damage to the pile material as the measured strains were very large.

The lateral load required to produce this deflection was 22% less than that required with no axial load. After 20 hours the relaxation in this load was 15% and a further 5% reduction occurred during the next 76 hours. The axial load increased the immediate pile deflections and also the time dependent pile and soil deflections. The deflections with a lateral load of 6.5 kN (0.65 ton) and axial load of 100 kN (10 ton) are shown in Fig. (6). The predicted deflections are shown in Fig. (2).

7 REPEATED LATERAL LOAD TESTS

A series of repeated loads were applied to the second pile. Initially the displacement was adjusted to maintain a constant load of 12.5 kN (1.25 tons). Equilibrium was reached after 144 hours. The pile was unloaded and immediately re-loaded to the same total load. No significant change in pile head displacement occurred on re-loading but some additional displacement was required to maintain the load. After two hours the pile was unloaded and reloaded. After several cycles creep effects were minimal and the same total displacement was produced by each load application.

At the first unloading of the pile it did not return to its original shape but at the end of each subsequent loading cycle it returned to the same intermediate shape on unloading.

8 CONCLUSIONS

These small section flexible steel piles were capable of supporting quite significant lateral loads. Large displacements and bending moments were developed at the pile head but these were rapidly diminished with depth below the soil surface.

The bending moments and deflections along the pile could be predicted with reasonable accuracy by an iterative analysis based on an assumed elastic-plastic soil behaviour for each layer of soil. A modified Winkler medium was used in which the soil stiffness was progressively adjusted to account for the soil non-linearity.

The appropriate soil modulus values can be determined from field tests on prototype piles by using the relationship between head sway displacement (Δ) and head rotation (θ). As the surface layer of soil controls the pile behaviour stiffness variations in the deeper layers of soil have little influence on the displacement of the pile head.

Axial load increases the deflections produced by the lateral load and should not be omitted from any analysis. It increases bending moments in the lower levels of the pile and causes greater creep or time dependent deformation of the soil.

In these tests the immediate deflection - load behaviour was substantially linear but creep in the supporting soil caused significant increases in the pile deflections. On repeated loading these creep deflections were reduced and the pile behaviour was essentially elastic.

9 ACKNOWLEDGEMENTS

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