

Design of Laterally Loaded Displacement Piles
Using a Driven Pressuremeter

P.K. Robertson¹, J.M.O. Hughes², R.G. Campanella³ and A. Sy⁴

Abstract

The non-linear subgrade reaction method is widely used for the design of laterally loaded piles. This method replaces the soil reaction with a series of independent springs. The non-linear behaviour of the soil springs is represented by "p-y" curves which relates soil reaction and pile deflection at points along the pile length. Most of the existing methods for obtaining p-y curves are highly empirical. Often little account is taken of the method of pile installation. The pressuremeter offers an almost ideal in-situ modelling tool for determining directly the p-y curves for a pile. As the pressuremeter can either be driven or self-bored into the soil, the results can be used to model either a displacement or a nondisplacement pile.

The driven pressuremeter used in the study described in this paper was essentially a standard pressuremeter with a solid 60° cone shoe at the tip. The instrument was pushed into the soil. This paper provides a detailed description of the equipment, testing procedures, and the theory that enables the family of p-y curves for laterally loaded displacement piles to be obtained. A case study using the driven pressuremeter results to predict and compare the performance of 2 full scale field lateral pile load tests is presented.

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Introduction

The non-linear subgrade reaction method is widely used for the design of laterally-loaded piles. This method replaces the soil reaction with a series of independent springs. The non-linear behaviour of the soil springs is represented by P-y curves, which relate soil reaction and pile deflection at points along the pile length. Most of the existing methods for obtaining P-y curves are highly empirical. Often little account is taken of the method of pile installation and the influence that this may have on the soil behaviour. The pressuremeter, however, offers the potential to measure the soil reaction in-situ, under similar loading conditions. The pressuremeter can also be installed to simulate the disturbance to the soil during pile installation.

This paper describes a case study where a pressuremeter was used to predict the results of a full-scale lateral load test on a displacement pile driven in soft peat and clay.

Test Site

The test site is located in a low-lying area southwest of Burnaby Mountain in Greater Vancouver, B.C.

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A summary of the soil profile based on sampling, laboratory testing and static cone penetration testing (CPT) is shown in Fig. 1. A 1.2 m thick loose gravelly sand fill covers the site. The surface fill is underlain by about 1.8 m of very soft peat with interbedded silt and sand layers. The peat is underlain by about 2.7 m of a soft medium plastic clayey silt. The silt is underlain by a dense glacial till. Groundwater is close to the original ground surface.

Lateral Load Tests

The test piles were 30 cm (12 inch) square precast concrete piles reinforced with four 2.5 cm (1 inch) diameter longitudinal steel bars and 1 cm (3/8 inch) diameter lateral steel ties. The concrete had a minimum unconfined compressive strength of 41 MPa (6000 psi) prior to installation. The calculated flexural rigidity or stiffness of the concrete pile, EI , is 23×10^6 MPa (3×10^9 lb.in.²).

To avoid tension cracks during driving, the piles were driven with a 2.7 Mg (6000 lb) drop hammer falling 30 cm (12 inches) when the pile end was penetrating through loose and soft soils, and 90 cm (36 inches) when the pile end was in glacial till. The pile penetration resistance diagrams of the 4 test piles are shown in Fig. 2.

The lateral load tests were carried out in general accordance with ASTM Standard D3966-91-81 by jacking apart two free-headed piles installed about 1.52 m (5 ft) apart and measuring their horizontal deflections. A 1200 kN (135 ton) capacity calibrated hydraulic jack was used for applying the test loads. Maximum 5 cm (2 inch) dial gauges referenced to 6 m (20 ft) long suspended I beams were used for measuring lateral pile deflections.

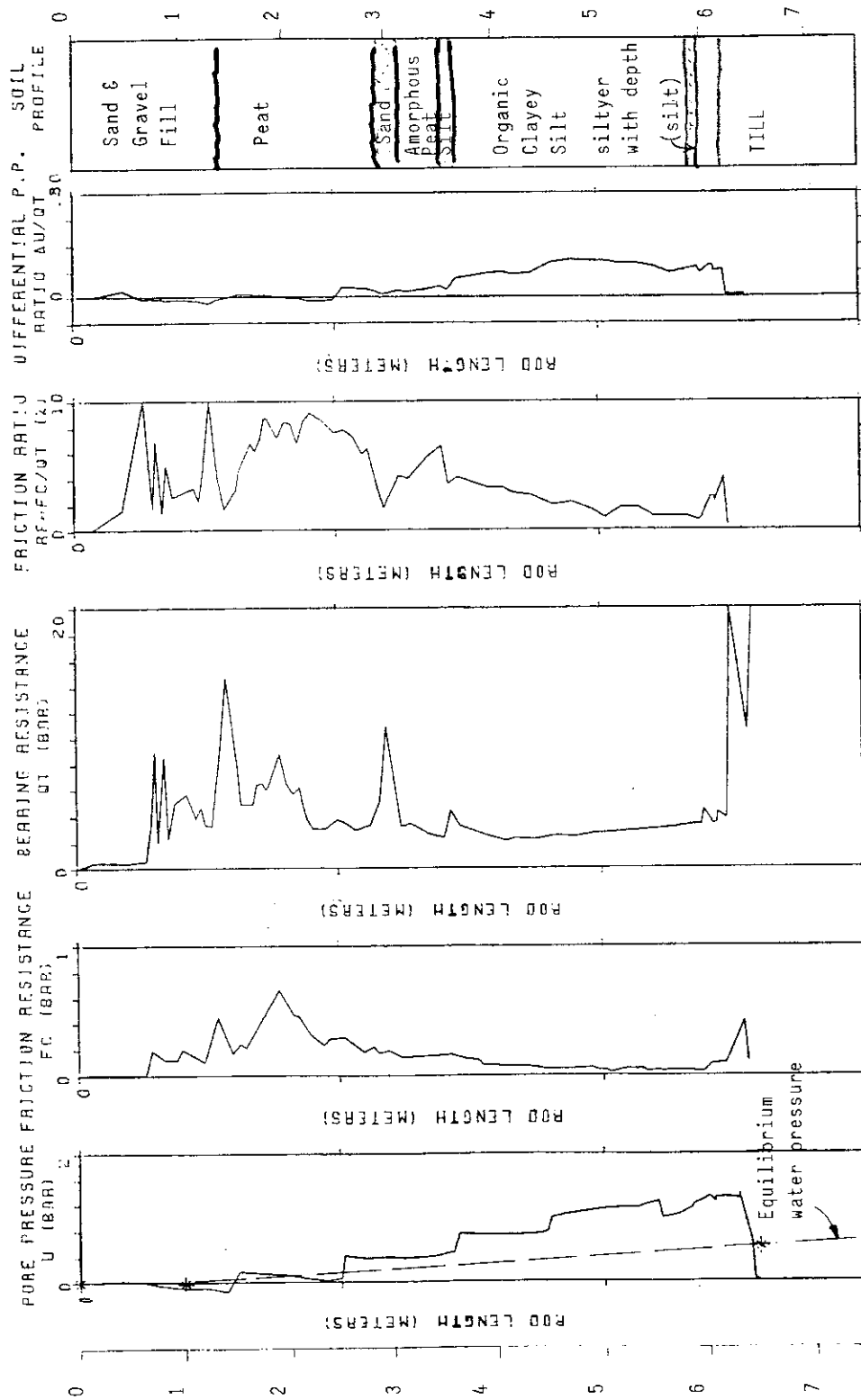


FIGURE 1 - Summary of Soil Profile

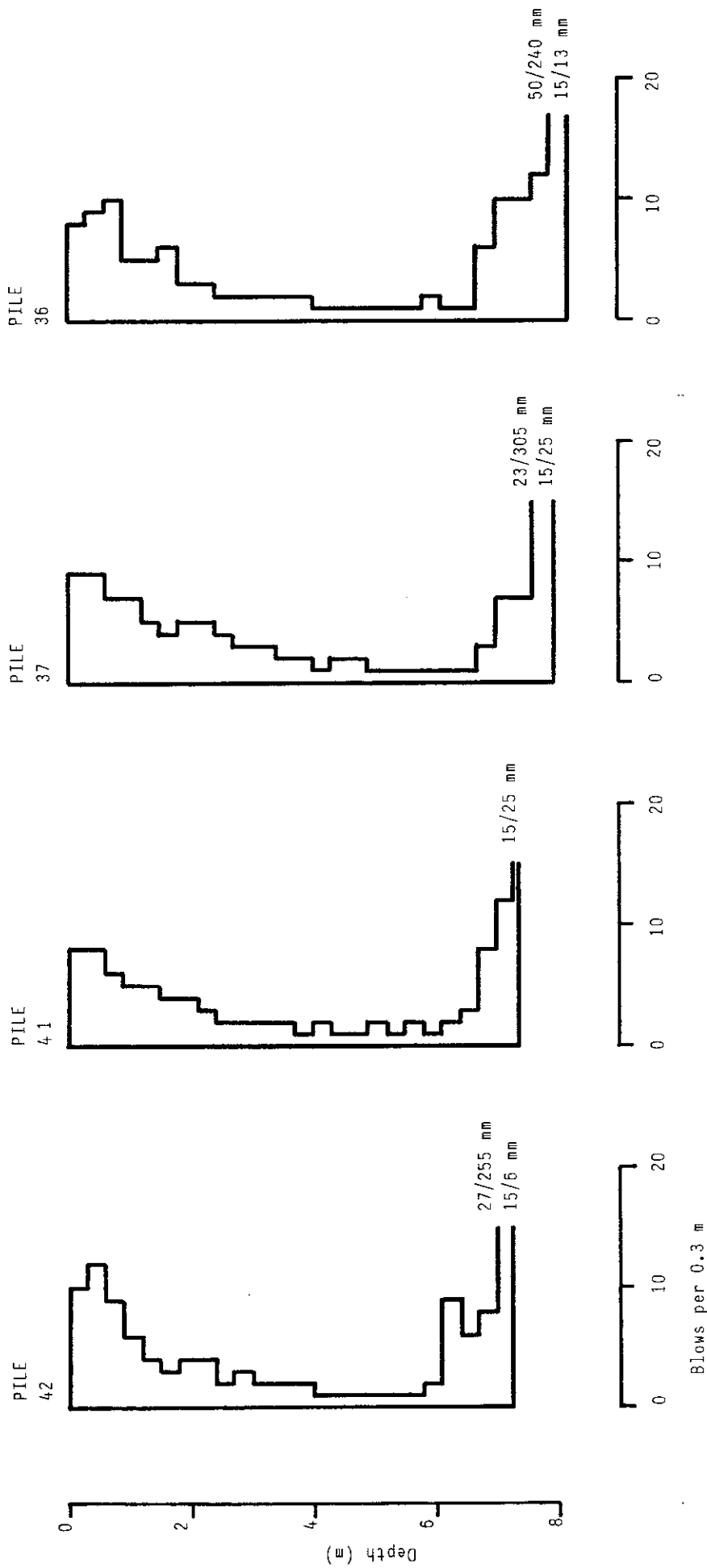


FIGURE 2 - Summary of Pile Penetration Diagrams

Load test No. 1 was performed on piles 36 and 37 with the load applied at the existing ground surface with approximately 1 m of loose gravelly sand around the pile heads. Load test No. 2 was performed on piles 41 and 42 with the load applied at the bottom of a 1 m deep excavation (i.e. at the original ground surface). Load test No. 2 was performed to assess the influence of the surface fill on the lateral displacement characteristics of the piles.

For both load tests, the lateral load was applied in increments, and was cycled through zero at different stages during the loading sequence. After the maximum test load was reached, the unloading was completed in steps.

After the initial loading cycle to 28 kN (6.29 kips) in load test No. 2, the test piles were subjected to 100 repetitive unloading-loading cycles to 28 kN (6.29 kips) before the test proceeded to the next higher load increment.

Each loading step was maintained for 1 to 2 minutes until movement was observed to be negligible. The repetitive loads were maintained for 15 to 30 seconds only.

The schematic lateral load test set up and the measured load versus deflection plots of the test piles are shown in Fig. 3.

It is interesting to note that in both load tests, the pile adjacent to the jack deflected slightly more than the other pile which was adjacent to the steel strut or spacer. This observed phenomenon could not be explained by the pile penetration resistances. It could be that friction between the steel plates/steel struts and the ground surface resulted in smaller loads transferred to the pile adjacent to the steel strut.

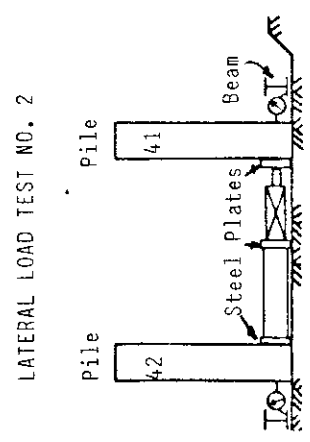
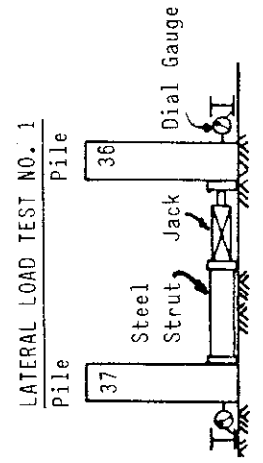
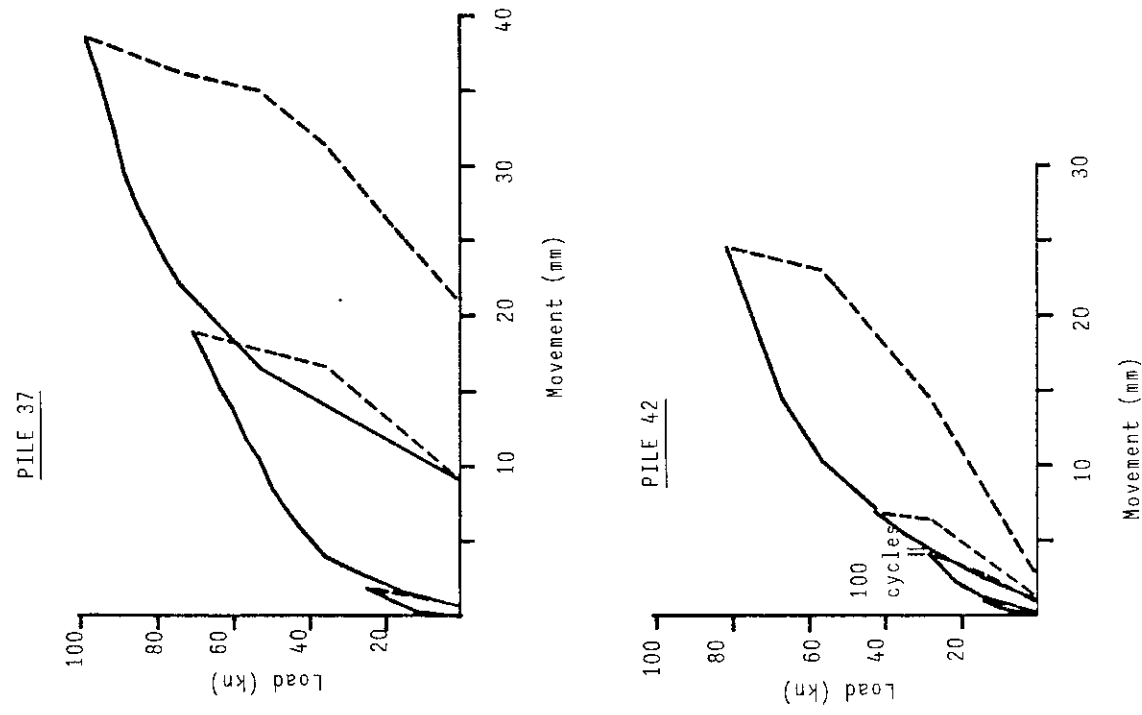
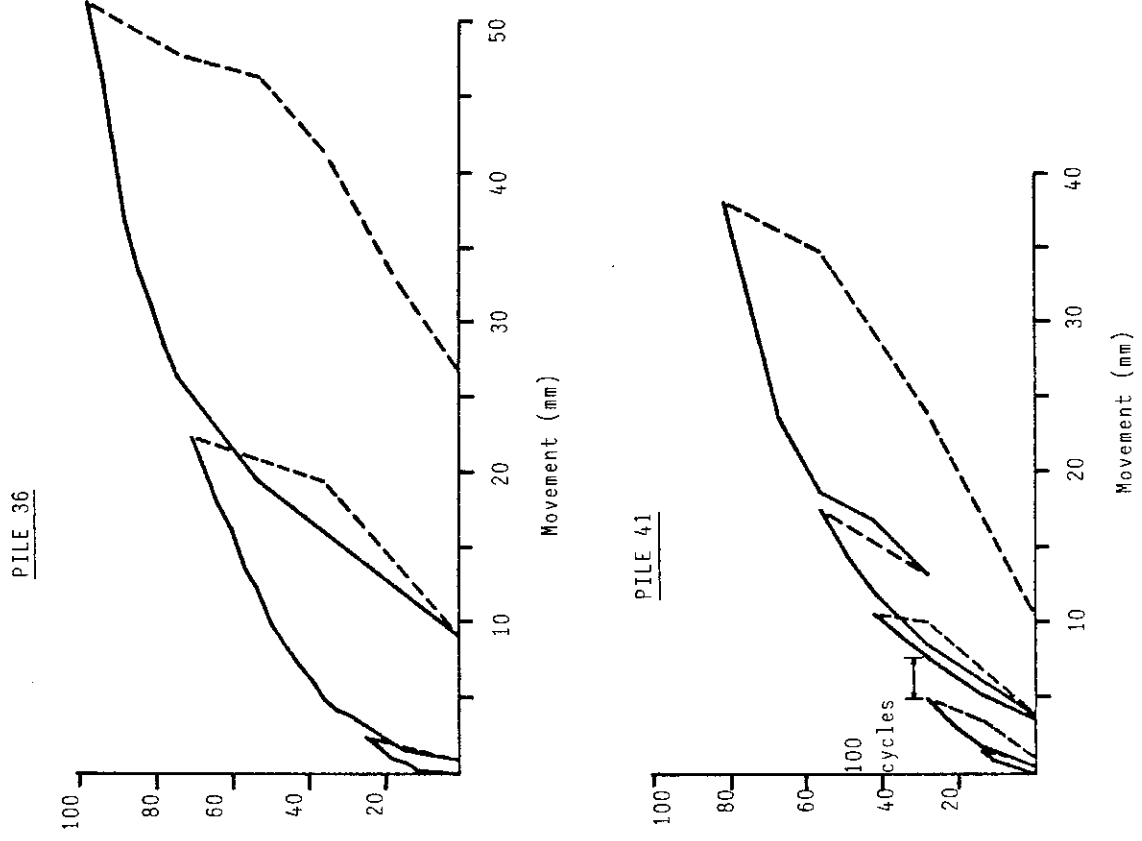


FIGURE 3 - Schematic Test Set Up and Load Versus Deflection Plots of Test Piles

Determination of the P-y curves

The evaluation of the P-y curves was from the results of pressuremeter tests. However, the pressuremeter was not installed in the usual manner, i.e. in a pre-drilled hole; it was pushed into the ground using a vehicle designed for conducting cone soundings. With this technique, the initial disturbance about the pressuremeter is very similar to the disturbance about a driven pile.

The pressuremeter was a standard self-boring pressuremeter with a solid 60° cone shoe at the tip. A schematic of the pressuremeter used during this study is shown in Fig. 4. The instrument was 76 mm in diameter with a length to diameter ratio, for the membrane section, of 6. The lateral displacements of the central portion of the expanding membrane were measured electrically. A conventional Menard type pressuremeter in which the displacements are measured by volume changes would have been satisfactory.

A total of 12 pressure expansion tests were performed at about 0.5 m intervals. The total time for these tests was approximately 5 hours.

Development of the P-y Curves from Pressuremeter Data

In the previous section, it was shown that the initial displacement induced in the soil surrounding a driven pressuremeter faithfully represents the displacements in the soil surrounding a driven displacement pile.

During the subsequent pressuremeter test, the soil deforms in a simple radial direction, whereas the displacements in the soil surrounding a laterally-loaded pile are far more complex as the soil moves away from the front face of the pile and in towards the back face. However, it could be

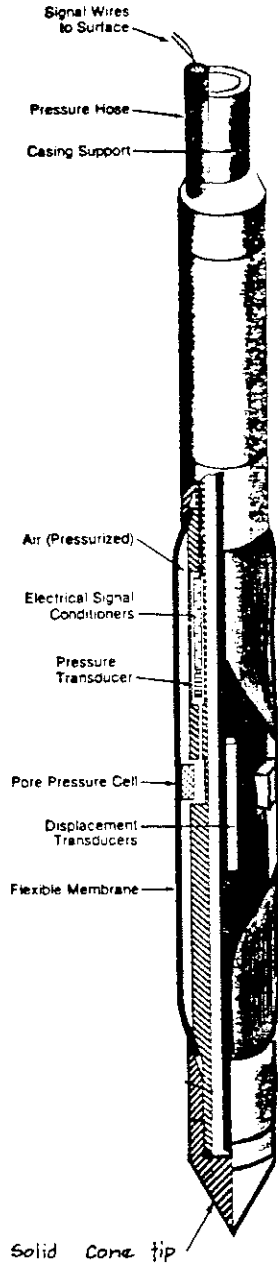


FIGURE 4 - Push-In Pressuremeter

expected that the soil in the centre region of the pile (A-B) in Fig. 5a would deform in a similar manner to that about a pressuremeter. Therefore, it would seem reasonable to suppose that the geometric form of the pressure expansion curve obtained from the pressuremeter would be similar to the load displacement P-y curves for the soil acting on the front face of the pile.

If curve P_0AP_L in Fig. 5b represented a typical test from a self-boring pressuremeter in which the probe was inserted into the soil with no disturbance, (i.e. a model of a non-displacement caisson pile), where P_0 is the initial stress and P_L is the limiting stress, then the geometric form of the P-y curve would be given by P_0AP_L , i.e. the origin for the pressure would be moved to P_0 (as shown in Fig. 5c).

The limiting pressure at which indefinite expansion occurs for the pressuremeter test ($P_L - P_0$) and the limiting pressure required to push a pile sideways through the soil are different.

If the section of the pile considered is at some distance remote from the surface, i.e. at a depth greater than about 4 pile diameters, then the limiting lateral resistance is approximately $9 c_u$, where c_u is the undrained shear strength, (Hansen, 1961; Matlock, 1970). Whereas in the case of the pressuremeter, the limiting pressure ($P_L - P_0$) is approximately $5 c_u$.

Therefore, for non-displacement piles in which the initial stress on the pile is the same as the initial stress in the ground, the pressuremeter curves obtained from self-boring pressuremeters have to be increased by about 2 to give the correct curves from which the P-y curves can be constructed. However, for driven displacement piles, the above simple procedure has to be adjusted slightly.

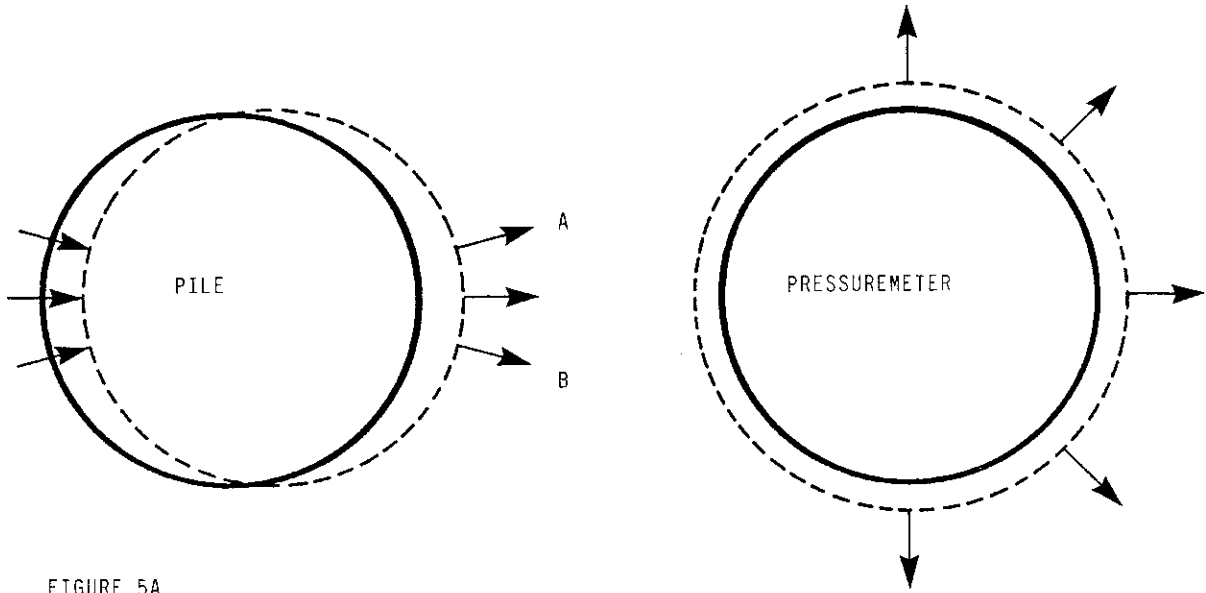


FIGURE 5A

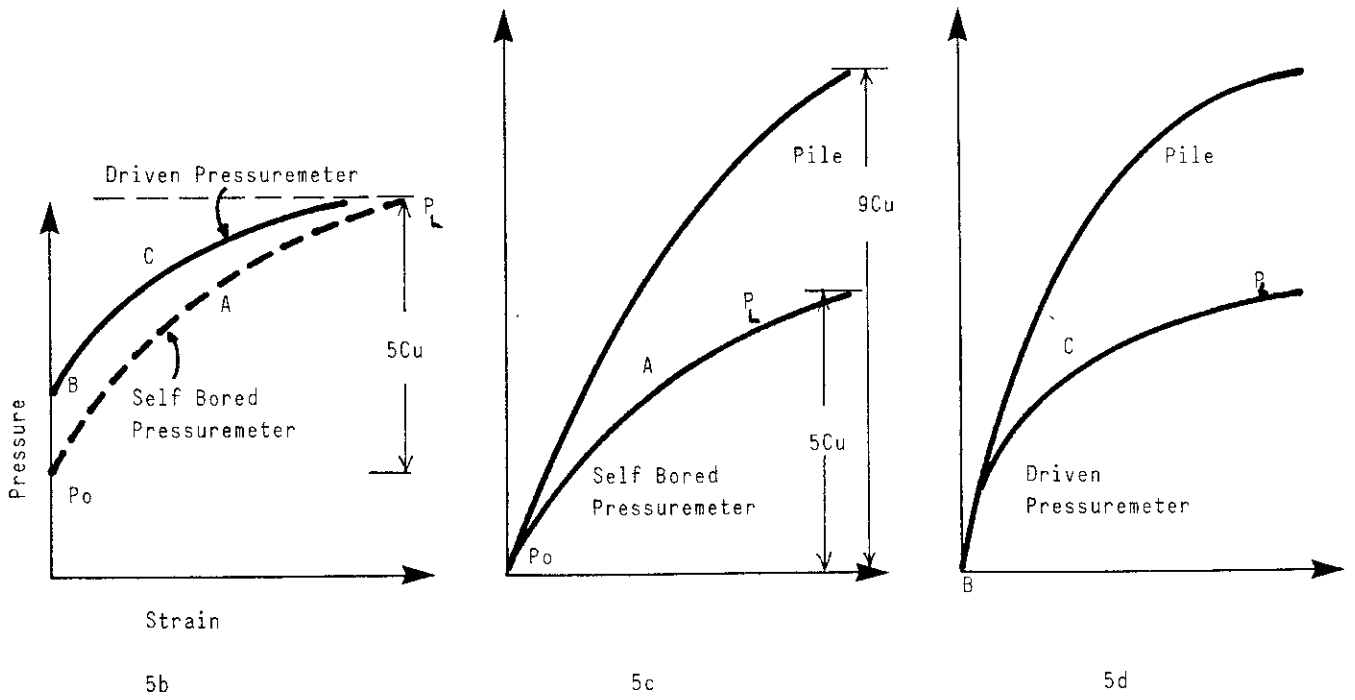


FIGURE 5 - Schematic Showing Development of P-Y Curves from Pressuremeter Data

It has been observed that the limiting pressure, P_L , in a pressuremeter test is almost independent of the method of installation of the probe. However, the initial stress before expansion, is dependent on the method of insertion. The result of an idealized pushed-in pressuremeter curve is given by BCP_L in Fig. 5b. The initial stress on the probe, point B, is above the in-situ lateral stress P_o . If it is assumed that the shape of the P-y curve follows the pressuremeter curves, then they must be magnified further, such that the limiting pressure still equals $9 c_u$.

In the following field example, the values of c_u used to evaluate the multiplication factors have been determined from the limiting pressures observed in the pressuremeter tests and the calculated in-situ stresses (P_o) using the following formula:

$$c_u = (P_L - P_o)/5$$

The P-y curves required for the analysis are in units of force per unit length (P) and displacement (y) whereas the pressuremeter curves are in units of stress (σ_r) and circumferential strain $\frac{(\Delta R)}{R}$, where R is the initial radius of the probe. Thus, to convert the pressuremeter stress to force per unit length, the stress data is multiplied by the pile width (i.e. 30 cm). The pressuremeter strain data is multiplied by the pile half-width (i.e. 15 cm) to obtain the displacement (y).

The evaluation of the P-y curves discussed above is for an element of the soil remote from the surface, i.e. about 4 pile diameters below ground surface. For points closer to the surface, the soil reaction is softer

(Matlock, 1970; Broms, 1964). In the following analysis, the forces (P) developed by the above procedure have been halved for the evaluation of the P-y curves in the upper peat.

Fig. 6 shows the location of the pressuremeter tests, and the location of the P-y curves used for the pile analysis. The analysis was completed using a computer program developed by L.C. Reese (1977) at the University of Texas.

The resulting load deflection curves, at the load point, are compared with the measured pile deflection in Fig. 7.

Summary

The pressuremeter data was used to provide data for the analysis of laterally-loaded single displacement piles in soft peat and organic clay. The pressuremeter was driven into the soil to model, as accurately as possible, the soil disturbance during pile driving. The tests are relatively simple to perform and if required, can be performed fast. The 12 tests reported in this paper were performed in a 5-hour period.

Although the tests discussed in this paper are limited, the agreement between the calculated and measured deflection is encouraging. Therefore the method proposed may have applicability in other situations.

References

- Broms, B.B., 1964, "Lateral Resistance of Piles in Cohesive Soils", Journal of the Soil Mechanics and Foundation Division, ASCE, SM3, May.
- Hansen, J.B., 1961, "The Ultimate Resistance of Rigid Piles Against Transversal Forces", Danish Geotechnical Institute Bulletin No. 12, Copenhagen.

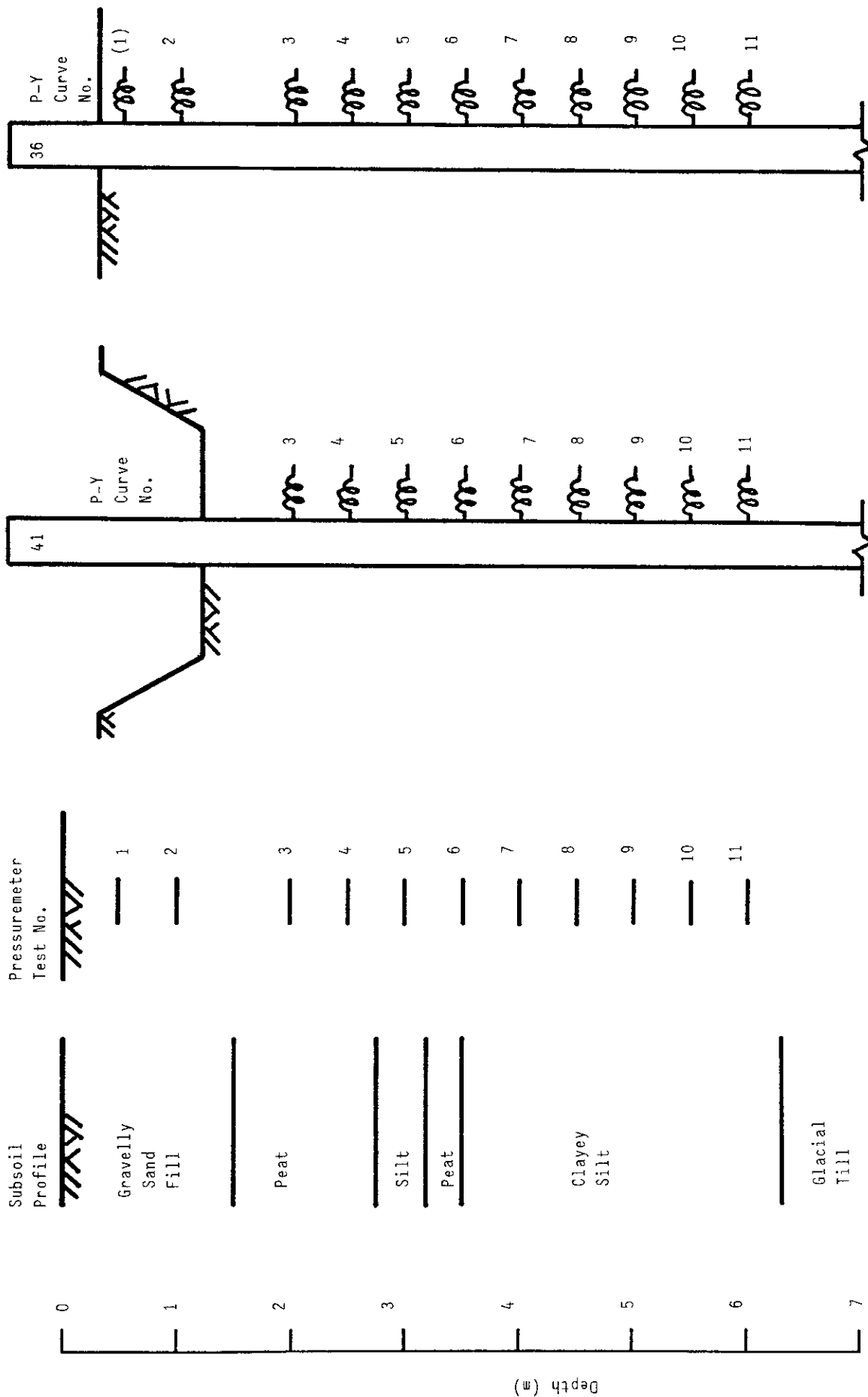


Figure 6 - Location of Pressuremeter Tests and P-Y Curves for Analysis

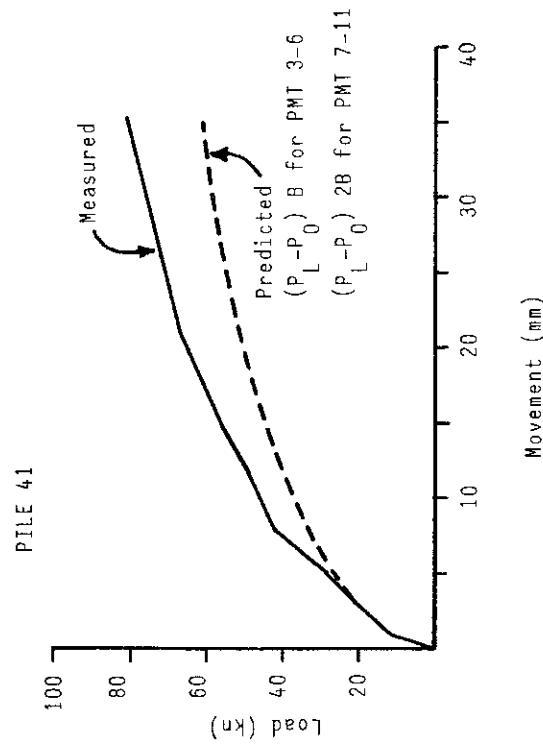
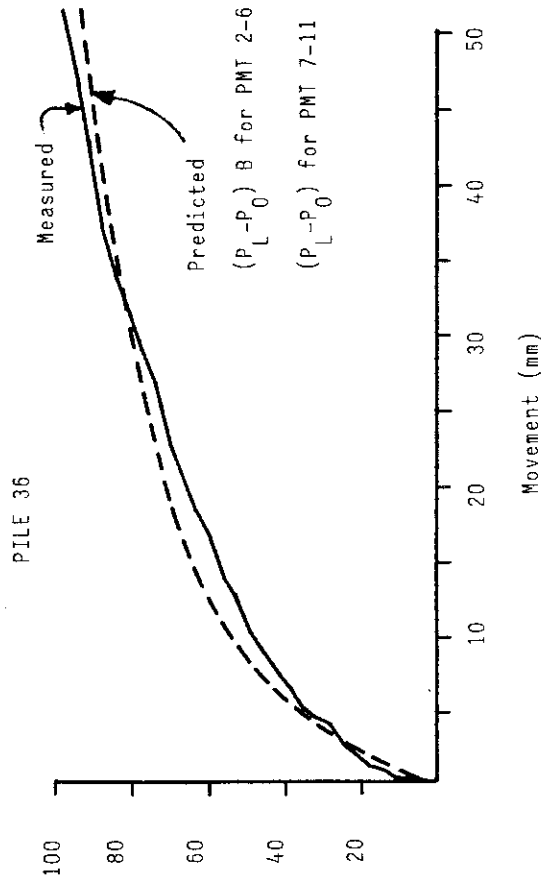


FIGURE 7 - Computed and Measured Load-Deflection Plots

- Matlock, H., 1970, "Correlations for Design of Laterally Loaded Piles in Soft Clay", Offshore Technology Conference, Vol. 1
- Reese, L.C., 1977, "Laterally Loaded Piles: Program Documentation", Journal of the Geotechnical Engineering Div., ASCE, Vol. 103, GT4, April, pp. 287-306.
- Reese, L.C. and Desai, C.S., 1977, "Laterally Loaded Piles", Chapter 9 of "Numerical Methods in Geotechnical Engineering", Desai and Christian, Editors, McGraw-Hill, New York.