

Peter K. Robertson, John M.O. Hughes, Richard G. Campanella, Peter Brown and Shawn McKeown

DESIGN OF LATERALLY LOADED PILES USING THE PRESSUREMETER

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ABSTRACT: The pressuremeter is ideally suitable for determining the in-situ non-linear parameters for the design of laterally loaded piles. A method for designing laterally loaded piles using pressuremeter data is presented. For driven displacement piles, which are commonly used offshore, the pressuremeter can be pushed into the soil in a similar full-displacement manner. Several case histories are presented to illustrate the proposed method.

KEY WORDS: pressuremeter, piles, lateral loading.

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 behavior 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.

Drs. Robertson and Campanella and Mr. P.T. Brown are NSERC University Research Fellow, Professor and student, respectively, in the Department of Civil Engineering, 2324 Main Mall, The University of British Columbia, Vancouver, B.C., Canada, V6T 1W5; Dr. Hughes is a consultant at 3009 St. Andrews St., N. Vancouver, B.C., Canada, V7N 1Z5; Mr. S. McKeown is an engineer with Golder Associates (Western Canada) Ltd., 7017 Farrell Road S.E., Calgary, Alberta, Canada, T2H 0T3.

Several methods have been proposed for the design of laterally loaded piles using pressuremeter data (Briaud et al. [1], Baguelin et al. [2], Imai [3], Robertson et al. [4], Baguelin [5]). Most of these methods make use of preboring pressuremeter results, using a Ménard type pressuremeter, and cannot model the disturbance caused from a driven pile since the pressuremeters are placed in a prebored hole. It is possible to install the pressuremeter in a manner which models the disturbance caused during pile installation. For driven displacement piles, the pressuremeter can be pushed into the soil in a full-displacement manner. For cast-in-place or bored piles, a pre-bored or self-bored pressuremeter test can model the disturbance during pile installation. The method by Robertson et al. [4,6] uses the results from a pressuremeter pushed into the soil to model the installation of a driven displacement pile.

During the pressuremeter test, the soil deforms in a simple radial direction, whereas the displacements in the soil surrounding a laterally loaded pile are more complex as the soil moves radially away from the front face of the pile and inwards towards the back face [7], as shown on Fig. 1. However, it is reasonable to expect that the soil in the center region of the front face of the pile would deform in a similar manner to that about a pressuremeter (see Fig. 1). Therefore, it is 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) curve for the soil acting on the front face of the pile, provided the pressuremeter was installed to model the soil disturbance during pile installation.

It is interesting to note from Fig. 1 that when a circular pile is loaded laterally, virtually all the soil displacements are radially away or toward the pile. There appears to be very little slip along the side of the pile to generate lateral friction.

Hughes et al. [8] suggested that the pressuremeter curves should be increased by some factor (α) to give the correct P-y curves for the pile. This multiplying factor is a factor to account for the fact that laterally loaded piles have limiting soil reactions that are higher than those for radially expanding pressuremeters. Hughes et al. [8] and Robertson et al. [4] suggested that the multiplying factors are as follows:

$$\alpha = 2 \quad \text{for cohesive soils} \quad (1)$$

$$\alpha = 1.5 \quad \text{for cohesionless soils} \quad (2)$$

These multiplying factors were also confirmed by Byrne and Atukorala [9] using finite element analyses. Further research and field evaluation, however, is still required to refine these numbers for many different soil types.

The multiplying factors (α) are applied to the pressure component of the pressure expansion curves, as shown in Fig. 2.

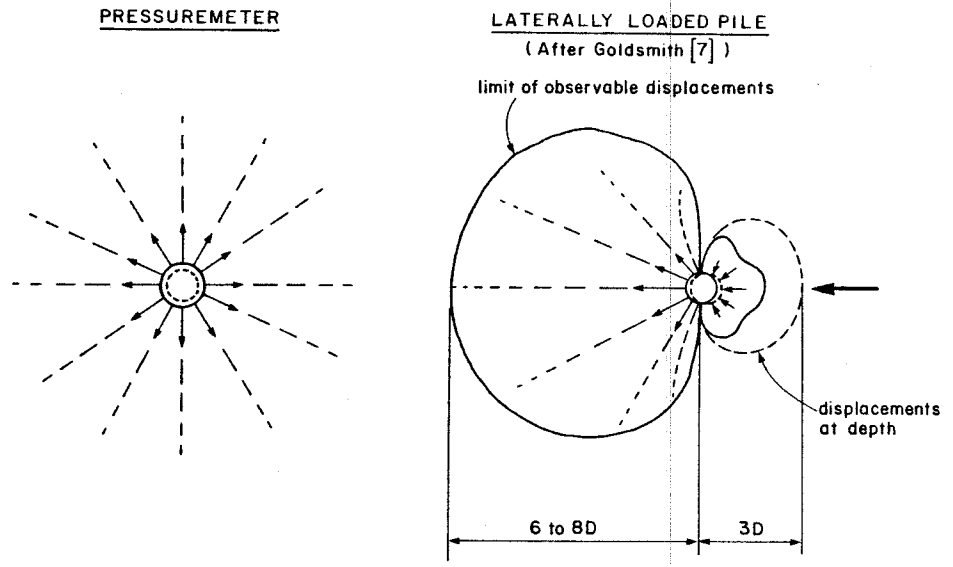


Fig. 1. Displacements in Soil around Radially Expanding Pressuremeter and Laterally Loaded Pile.

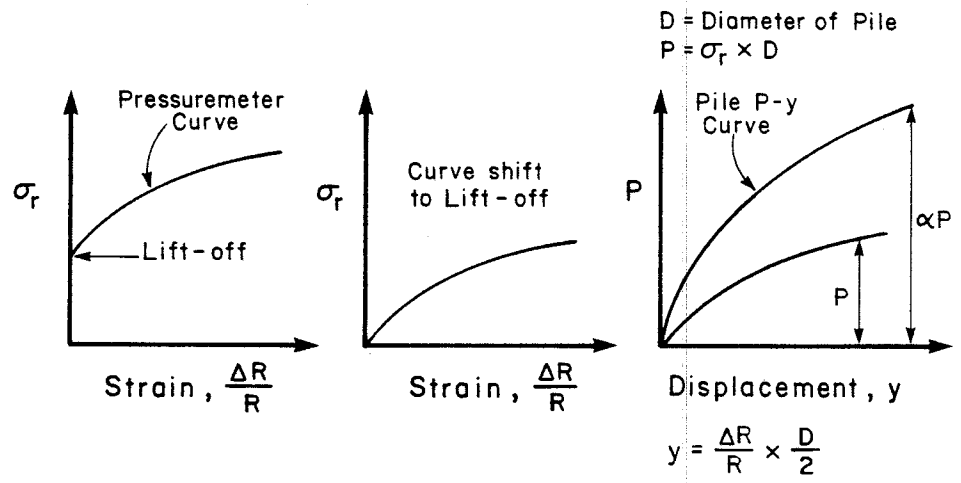


Fig. 2. Schematic Representation of Development of Pile P-y Curves from Pressuremeter Curves.

The lateral stresses acting against the sides of the pile will be influenced by the pile driving and subsequent waiting or set-up period. The pile is in equilibrium with the lateral stresses, therefore, with the application of a lateral load, the pile will immediately start to move. However, when a pressuremeter is installed, the pressure inside the probe is increased from zero until the membrane is in equilibrium with the soil and expansion starts. By installing the pressuremeter in a similar manner, the pressure expansion curve will have a lift-off pressure approximately equivalent to the initial lateral stress around the pile. Therefore, to obtain the subsequent P-y curve for lateral loading, the pressure axis for the P-y curve is moved to the lift-off pressure from the pressuremeter curve, as shown on Figure 2.

In fine grained soils, such as silty sands, silts and clays, significant pore pressures can be generated during driving of a pile. These pore pressures usually dissipate before any lateral loads are applied to the pile. If the pressuremeter is to be used as a model for the pile, the excess pore pressures generated during the installation of the pressuremeter must also be allowed to dissipate before expanding the membrane.

The time required for excess pore pressures to dissipate around a cylindrical probe is proportional to the radius of the probe squared. Therefore, the time required for a significant portion of the pore pressures to dissipate around a pressuremeter depends on the diameter of the instrument. Most pressuremeter probes are in the order of 75 mm in diameter. Some pressuremeters are as small as 44 mm in diameter. Therefore, the time required for significant pore pressure dissipation around most pressuremeters is usually less than about 30 minutes for most silty soils. Longer times are required for low permeability clays. Smaller times for dissipation are required for smaller diameter probes. If piezo-cone penetration testing is available, the time required for dissipation of excess pore pressures around the pressuremeter can be estimated from a dissipation test using the cone.

The approach given above can be applied to pressuremeter tests performed at some depth remote from the surface. Near the surface, the displacements of both the laterally loaded pile and the expanding pressuremeter can be influenced by the surface. The pressuremeter is subject to a reduction in the mobilized resistance at shallow depth. The critical depths (z_c) as recommended by Baguelin et al. [2] are:

$$z_c = 15 D_{PMT} \quad \text{for cohesive soils} \quad (3)$$

$$z_c = 30 D_{PMT} \quad \text{for cohesionless soils} \quad (4)$$

where D_{PMT} = diameter of pressuremeter.

Therefore, for 75 mm diameter pressuremeters, the pressure values of the pressuremeter test results require some increase due to surface effects to a depth of between 1.1 m to 2.2 m. The suggested reduction factors given by Briaud et al. [1] are shown in Fig. 3. The pressuremeter curve is then corrected by using:

$$P_{corr} = \frac{P}{\beta} \tag{5}$$

where P_{corr} = corrected pressure.
 β = reduction in mobilized pressuremeter pressure at all strains.

The correction is only applied to pressuremeter test results that may be influenced by the close proximity of the ground surface. The depth of the pressuremeter should be based on the position of the center of the membrane.

The displacements of soil around a laterally loaded pile are also influenced by the ground surface. The critical depth (D_c), to which displacements are influenced, depend on the pile load, diameter and stiffness. Briaud et al. [1] proposed a relative rigidity factor, RR, given by:

$$RR = \frac{1}{B} \sqrt[4]{\frac{EI}{P_L}} \tag{6}$$

where EI = pile flexural stiffness
 B = pile diameter
 P_L = net pressuremeter limit pressure.

The correlation between the ratio of critical depth to pile diameter and RR proposed by Briaud et al. [1] is shown on Fig. 4.

For most prebored pressuremeter tests, there is a clear definition of the net pressuremeter limit pressure, P_L . However, for self-bored or full-displacement pressuremeter tests in sandy soils, there is not always is a clear definition of P_L .

Robertson et al. [6] suggested using a general critical depth of four pile diameters ($D_c = 4$). However, the relationship proposed by Briaud et al. [1] in Fig. 4 is more logical and is recommended since it shows that for a high relative rigidity, ($RR > 10$), i.e. a stiff pile relative to the soil, the critical depth will be slightly larger than 4 and for flexible piles, the critical depth can be less than 4.

To account for the reduced soil reaction mobilized within the pile's critical depth, the multiplying factors are progressively reduced. Based on a review of experience in the literature, the writers recommend that the factors be reduced from a value of 2 at the pile critical depth to 0.67 at the ground surface for cohesive soils and from 1.5 down to 0 for cohesionless soils, as shown on Fig. 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 and ΔR is the change in radius. Thus, to convert the pressuremeter stress to force per unit

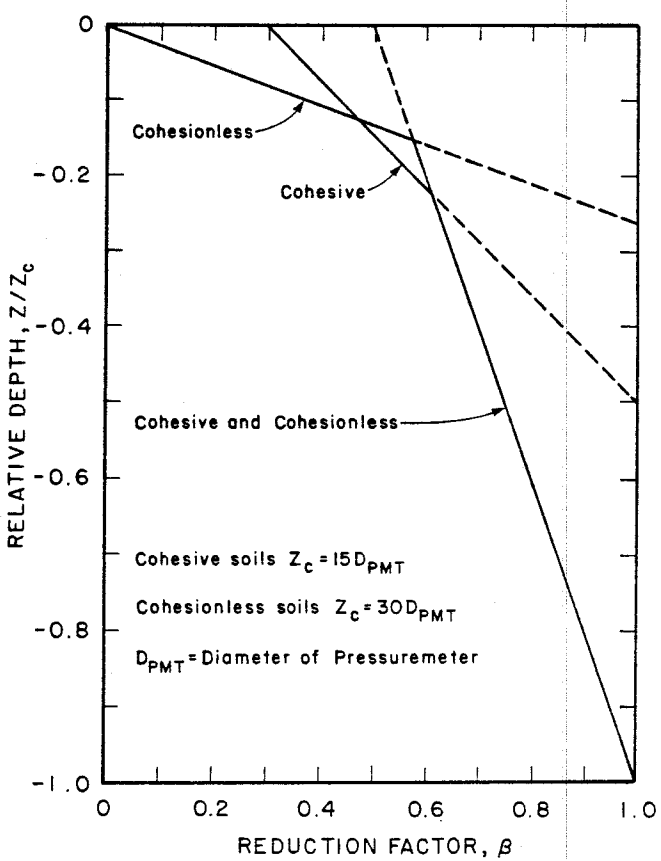


Fig. 3. Reduction Factors for Pressuremeter Test Results at Shallow Depth. (After Briaud et al. [1])

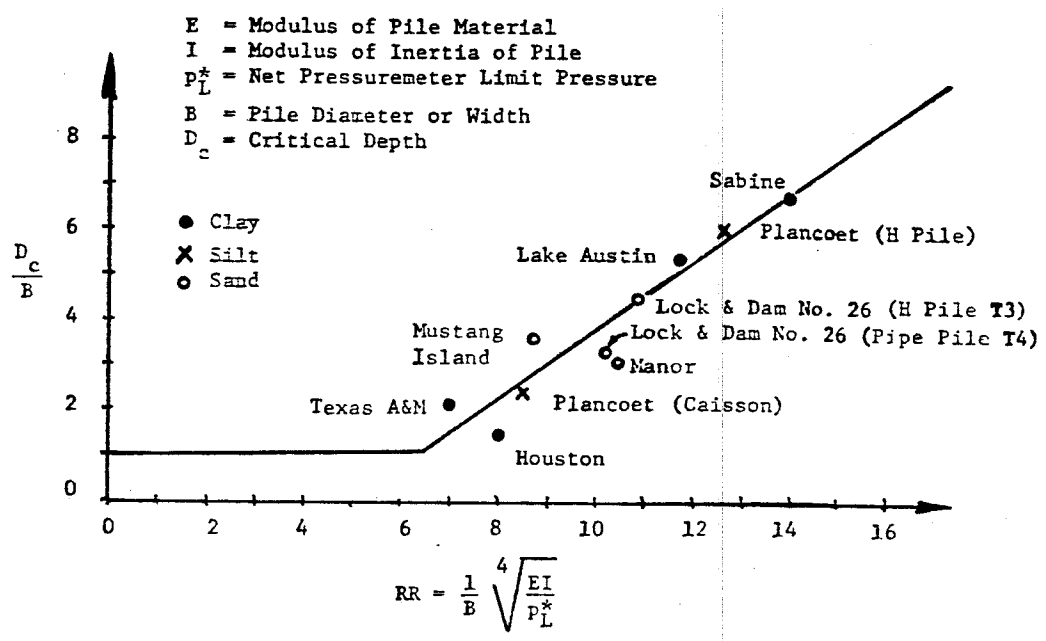


Fig. 4. Critical Depth of Laterally Loaded Pile as a Function of Relative Rigidity. (After Briaud et al. [1])

length, the stress data is multiplied by the pile width. The pressuremeter strain data is multiplied by the pile half-width to obtain the displacement (y), as shown on Fig. 2.

CASE HISTORIES

The writers have been involved in several case histories in recent years where the above method has been applied. The following sections will briefly present the results of these case histories.

Burnaby Mountain, B.C.

Full-displacement pressuremeter tests were performed to model the behaviour of four 300 mm square precast concrete piles driven to a depth of 8 m. The soil conditions consisted of 1.5 m of sand and gravel fill overlying 4.5 m of organic peat and silt. The piles were 6 m in length and driven end bearing onto a dense glacial till. Full details of the case history is given by Robertson et al. [4].

A summary of the calculated and measured load deflection curves at the ground surface are shown in Fig. 6.

The predicted deflection shows good agreement with the measured deflection for both test piles.

Annacis Crossing, B.C.

Full-displacement pressuremeter tests were performed to model the behaviour of a 915 mm diameter steel pipe pile driven open-ended to a maximum depth of 94 m. Full details of the case history is given by Robertson et al. [6]. A summary of a CPT profile showing pressuremeter test locations is given on Fig. 7. Also included in Fig. 7 is a summary of the multiplication factors (α) used in the calculation of the P-y curves.

A summary of the calculated and measured load deflection curves at the pile head and the pile deflection versus depth at a lateral load of 1100 kN are given in Figs. 8 and 9. The predicted deflection agrees remarkably well with the measured deflection and is approximately 20% larger at the pile head. It is worth noting that the prediction of lateral behavior was based solely on the pressuremeter and CPT results before the measured results were made available from the lateral load test. The predictions were based on the approach described above.

Calgary, Alberta

Self-bored pressuremeter tests were performed to model the behaviour of cast-in-place reinforced concrete piles. The piles

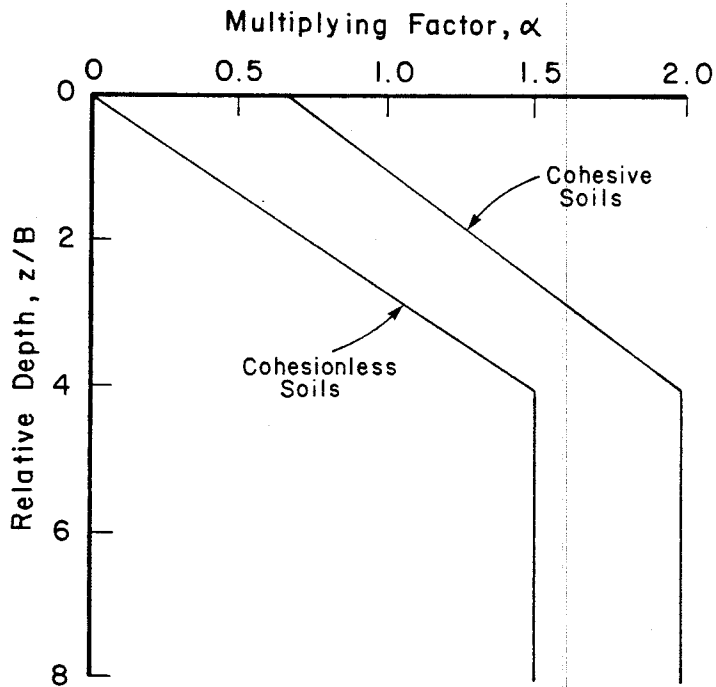


Fig. 5. Variation of Multiplying Factor with Relative Depth.

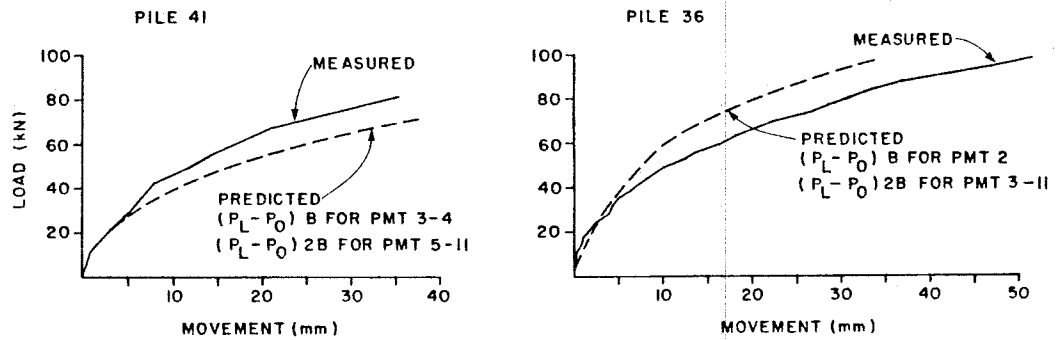


Fig. 6. Summary of Computed and Measured Load Deflection Curves at Ground Surface for Burnaby Mountain, B.C., Test Piles.

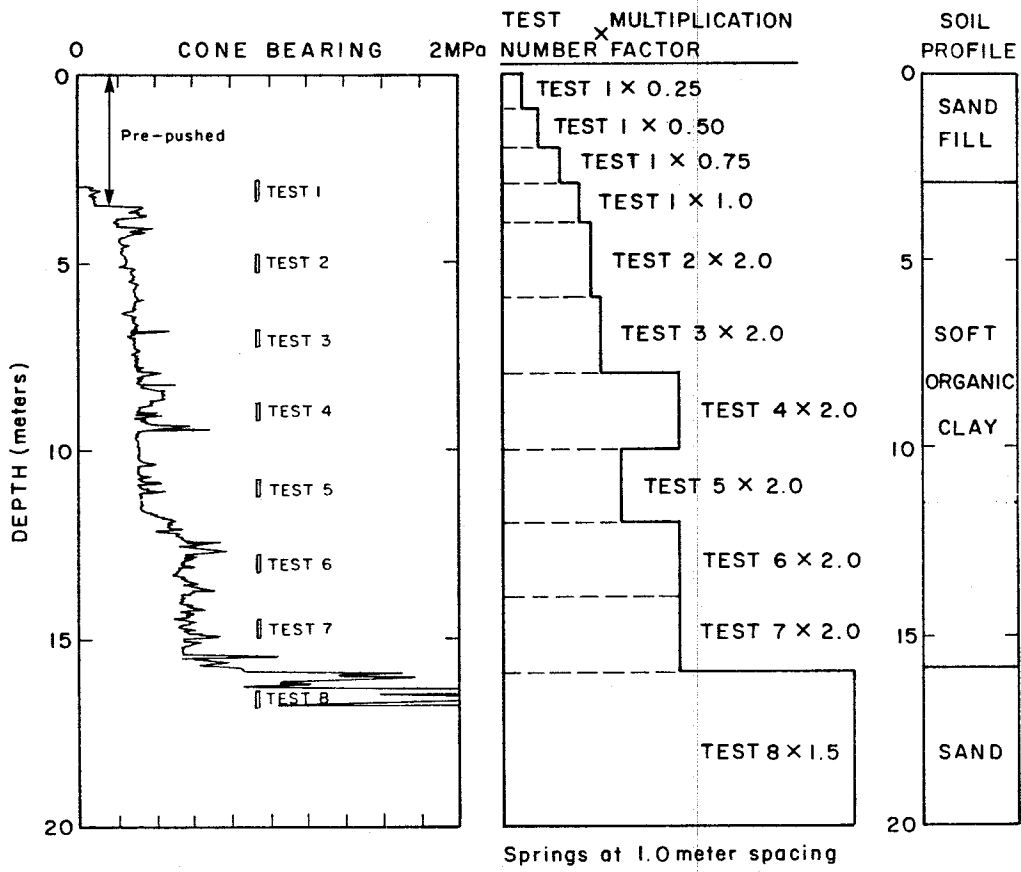


Fig. 7. Summary of CPT Profile Showing Pressuremeter Test Locations and Soil Spring Stiffness at Annacis Crossing, B.C., Site.

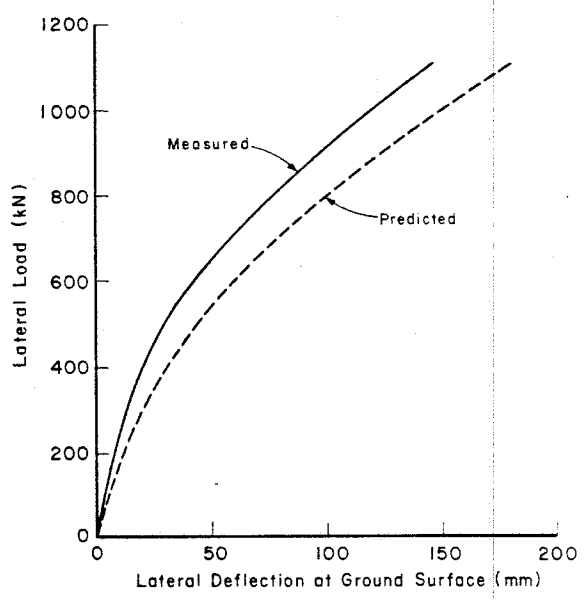


Fig. 8. Summary of Computed and Measured Load Deflection Curves at Ground Surface, for Annacis Crossing, Test Pile.

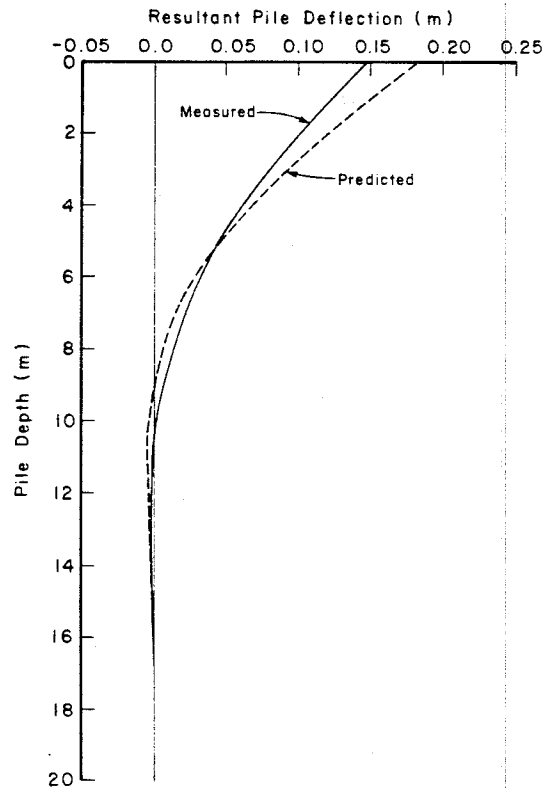


Fig. 9. Summary of Computed and Measured Lateral Pile Deflection versus Depth at a Lateral Load of 1100 kN for Annacis Crossing Test Pile.

varied in size and were 1.5 m, 1.2 m and 0.9 m in diameter, and installed to a depth of 15 m. A summary of a CPT profile showing pressuremeter test locations is given in Fig. 10. Also included in Fig. 10 is a summary of the multiplication factors (α) used in the calculation of the P-y curves.

The deflected shapes calculated from the pressuremeter tests for the free head piles showed good agreement with the observed pile deformations at the design loads. This is shown in Fig. 11 (a and b) for piles of diameter 1.5 and 0.9 m respectively. For the maximum test load, the computer analysis underestimated the total deflection (see Fig. 11a). The authors [10] considered this to be primarily due to the fact that the pile load test was carried out over a long period of time whereas the pressuremeter test was of short duration. Load-deflection-creep data was recorded for each pile and when creep deformations are taken out of the total pile deflections, the predicted and observed deflection are comparable. The authors [10] noted, however, that very little creep deformation occurred at less than the design load and that the pressuremeter model was considered appropriate for the piles tested.

It is worth noting that an evaluation of the creep behavior can be estimated from pressuremeter tests if the pressure during inflation is maintained constant and the rate of strain is recorded. These 'creep tests' can be performed at different stress levels.

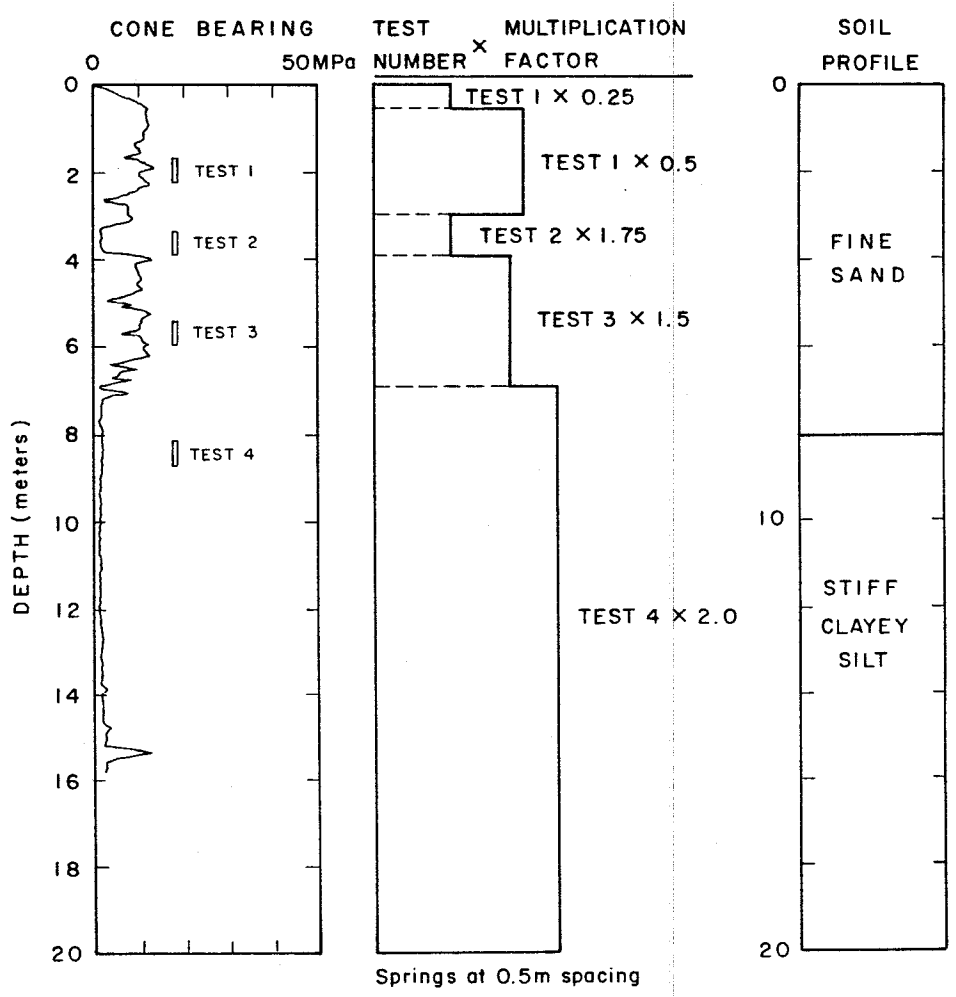


Fig. 10. Summary of CPT Profile Showing Pressuremeter Test Locations and Soil Spring Stiffness at Calgary, Alberta, Site.

Fraser River, B.C.

Full-displacement pressuremeter tests were performed to model the behaviour of a 324 mm diameter steel pipe pile driven open-ended to a depth of 18 m in a Fraser River sand deposit. The pile was installed at an incline of 3 vertical to 1 horizontal and loaded horizontally 600 mm above the ground surface. Full details of the case history are given by Brown [11]. A summary of a CPT profile showing pressuremeter test locations is given in Fig. 12. Also included in Fig. 12 is a summary of the multiplication factors (α) used in the calculation of the P-y curves.

A summary of the calculated and measured load deflection curves at the pile head are shown in Fig. 13. The horizontal lateral load was resolved perpendicular to the test pile for the analysis to account for the pile inclination.

It is interesting to note that significant creep deformation took place at large lateral loads during the lateral load test. If the creep deformations at the larger loads are taken out of the total pile deflections, the predicted and observed deflections are more compar-

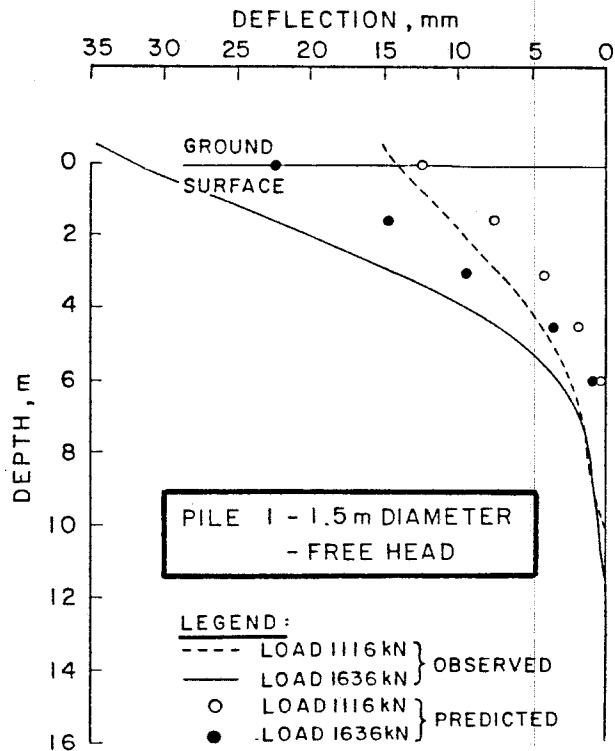
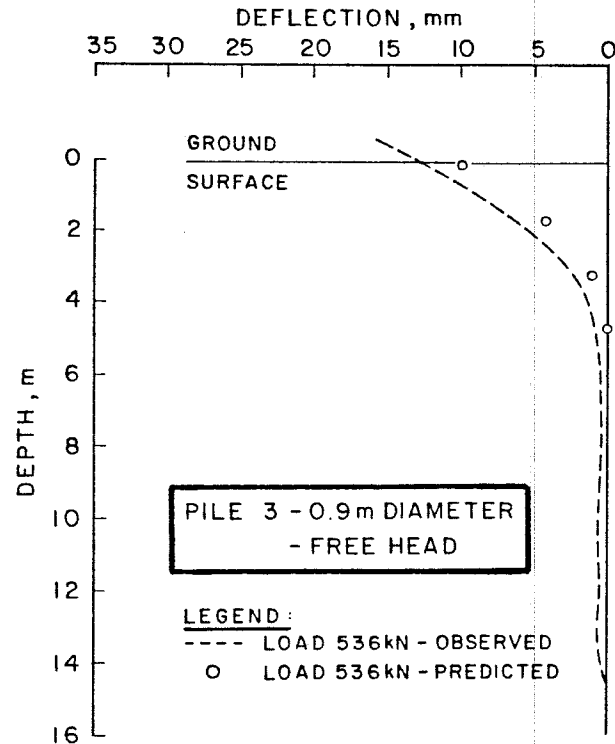


Fig. 11. Summary of Computed and Measured Lateral Pile Deflection versus Depth for 1.5 m and 0.9 m Diameter Piles at Calgary, Alberta, Site.

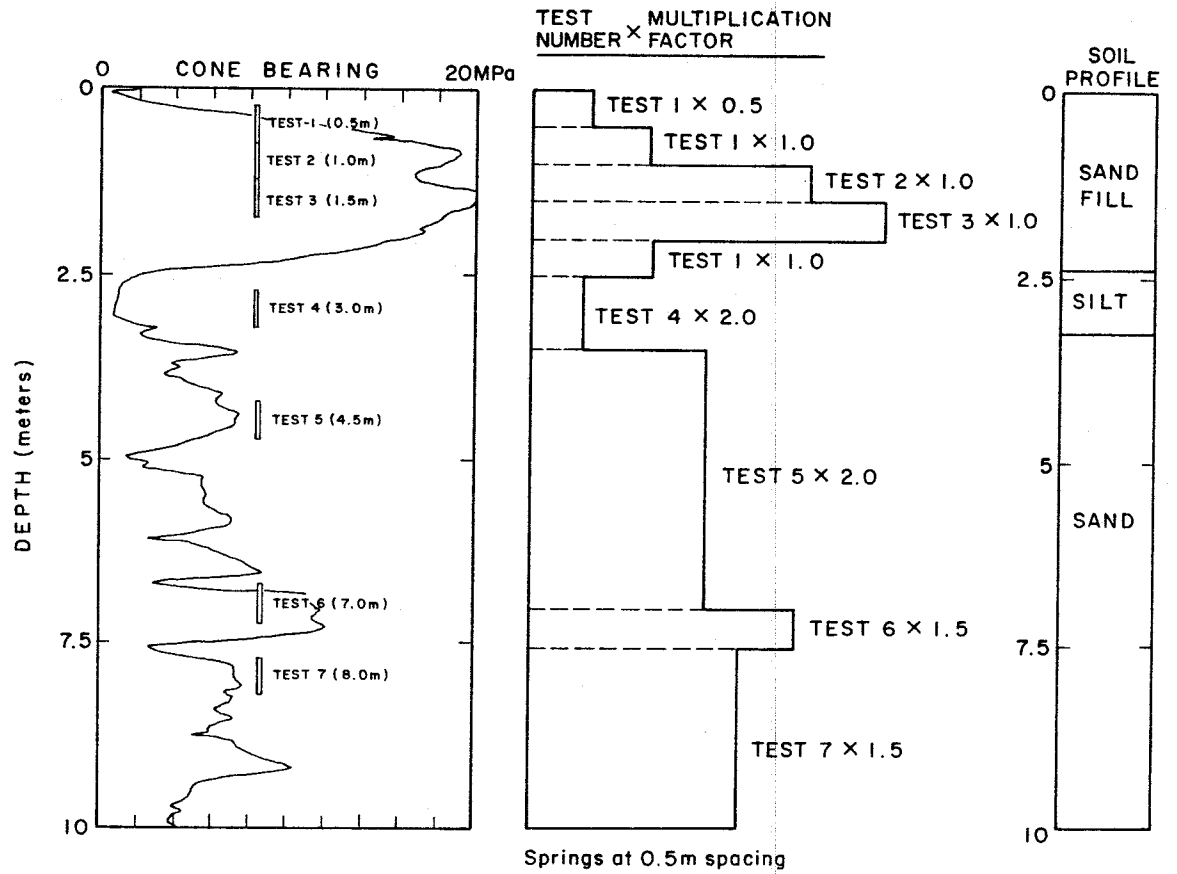


Fig. 12. Summary of CPT Profile Showing Pressuremeter Test Locations and Soil Spring Stiffness at Fraser River, B.C., Site.

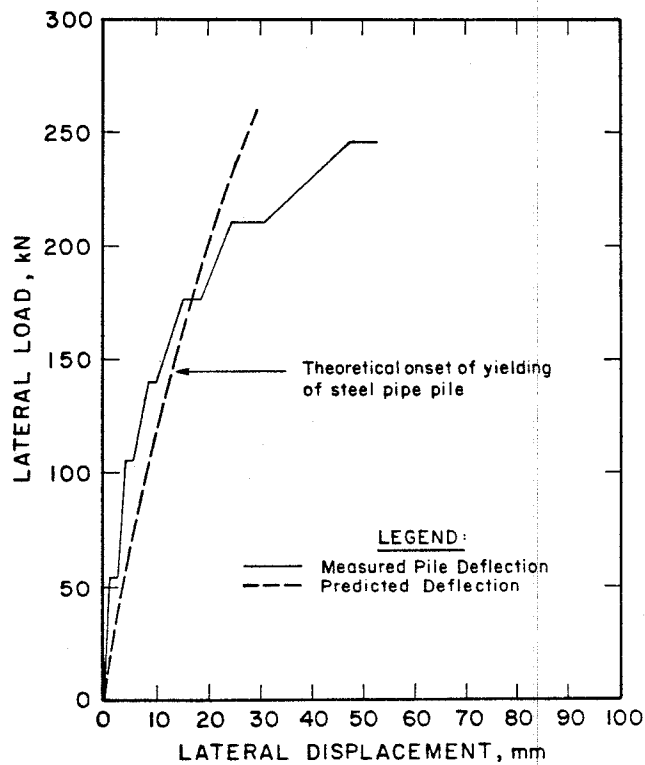


Fig. 13. Summary of Computed and Measured Lateral Load Deflection Curves for Fraser River Test Pile.

able. The effects of creep should be investigated if piles are to experience large lateral loads.

SUMMARY

A method for designing laterally loaded piles using pressuremeter data has been briefly summarized. Four case histories have also been presented to illustrate the method.

For a rational use of pressuremeter data for design of laterally loaded piles, the pressuremeter should be installed to model the soil disturbance during pile installation. For driven displacement piles, which are commonly used offshore, the pressuremeter should be pushed into the soil in a full-displacement manner. The correction factors required to adjust the pressuremeter curves to generate P-y curves have been discussed and preliminary values given. The corrections required for different soil types and the stress free surface effects require further evaluation. However, the case histories presented illustrate that the method and existing correction values suggested do provide excellent predictions of the behavior of laterally loaded piles. The proposed method was generally able to predict the lateral deflection at the ground surface and the overall deflected shape of the test piles to within 20% of the measured values. Further field evaluation is required to study the effects of long duration, creep, loads and cyclic loading. However, recent field work (Brown, 1985) has shown the potential of the pressuremeter to provide qualitative data on both creep and cyclic loading effects.

The ease of performing full-displacement pressuremeter tests offshore depends somewhat on the diameter of the probe since the pushing force to install the probe increases with increasing size. Research and development is presently underway at the University of British Columbia and Fugro, Holland to combine a 44 mm diameter (15 cm² base area) pressuremeter probe with an electric piezometer cone of the same diameter. This would enable the pressuremeter to be installed by currently available offshore CPT equipment. The CPT would also provide valuable data on the soil profile and assist in the optimum choice for pressuremeter test locations. The case histories presented have illustrated the usefulness of the combined CPT and pressuremeter. The CPT profile often provides confidence in the variation of pressuremeter test results [6] due to variable soil stratigraphy.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Briaud, J.-L., Smith, T.D. and Meyer, B.J., 1983, "Laterally Loaded Piles and the Pressuremeter: Comparison of Existing Methods", ASTM Special Technical Publication STP 835 on the Design and Performance of Laterally Loaded Piles and Pile Groups, June.
- [2] Baguelin, F., Jezequel, J.F. and Shields, D.H., 1978, The Pressuremeter and Foundation Engineering, Trans. Tech. Publications, Rockport, Mass.
- [3] Imai, T., 1982, "The Estimation Method of Pile Behaviour Under Horizontal Load using LLT Test Results", Proceedings of the Symposium on The Pressuremeter and Its Marine Applications, Paris, 1982.
- [4] Robertson, P.K., Hughes, J.M.O., Campanella, R.G. and Sy, A., 1983, "Design of Laterally Loaded Displacement Piles using a Driven Pressuremeter", ASTM STP 835, Design and Performance of Laterally Loaded Piles and Pile Groups, June, Kansas City, Mo.
- [5] Baguelin, F., 1982, "Rules for the Structural Design of Foundations Based on the Selfboring Pressuremeter Test", Symposium on the Pressuremeter and its Marine Applications, Paris, April.
- [6] Robertson, P.K., Campanella, R.G., Brown, P.T., Grof, I. and Hughes, J.M.O., 1985, "Design of Axially and Laterally Loaded Piles using In-situ Tests: A Case History", Canadian Geotechnical Journal, Vol. 22, No. 4.
- [7] Goldsmith, P.P., 1979, "Aspects of Soil-Pile Interaction under Static Loads", Ph.D. Thesis, University of Auckland, New Zealand.
- [8] Hughes, J.M.O., Goldsmith, P.R. and Fendall, H.D.W., 1979, "Predicted and Measured Behaviour of Laterally Loaded Piles for the Westgate Freeways Melbourne", a paper presented to the Victoria Geomechanics Society, Australia, August.
- [9] Byrne, P.M. and Atukorala, U., 1983, "Prediction of P-y Curves from Pressuremeter Tests and Finite Element Analyses", University of B.C., Civil Eng. Dept., Soil Mechanics Series No. 66.
- [10] Clark, J.I., McKeown, S., Lester, W.B. and Eibner, L.J., 1985, "The Lateral Load Capacity of Large Diameter Concrete Piles", Proceedings of the 38th Canadian Geotechnical Conference, Edmonton.
- [11] Brown, P.T., 1985, "Predicting Laterally Loaded Pile Capacity Using the Pressuremeter", M.A.Sc. Thesis, University of British Columbia, Dept. of Civil Engineering.