Analyses of Laterally Loaded Drilled Shafts Using In Situ Test Results

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To predict the lateral load-displacement response of small-diameter drilled shafts in desiccated clays, a series of in situ tests was performed at a field test site in Massena, New York. These tests included piezocone, flat dilatometer, field vane, and prebored pressuremeter. Four cast-in-place concrete shafts with diameters of 152 and 305 mm and lengths of 1.5 to 3.0 m were installed at the site. Predictions of the lateral load-deformation relationships were made prior to the pile load tests using a finite difference program and results from in situ tests. Comparisons were made between the predicted and the measured response of each drilled shaft. This paper describes the use of in situ tests in the analyses of relatively small and short, laterally loaded drilled shafts in desiccated clays and presents a discussion of the efficacy of the approach.

Many methods are available for analyzing single laterally loaded piles. They vary from relatively simple closed-form solutions (*1,2*) to sophisticated three-dimensional finite element techniques (*3*). A common approach is to treat the pile-soil system as a linear elastic beam resting on a series of Winkler springs that have nonlinear force-displacement relationships (*4*). The problem of a laterally loaded pile can then be described by a differential equation:

$$EI\frac{d^4y}{dx^4} + P_x\frac{d^2y}{dx^2} - p = 0 \tag{1}$$

and

$$p = E_s(x,y)y \tag{2}$$

where

P_x = axial load,
y = lateral deflection of pile,
x = length along the pile,
p = soil reaction,
EI = flexural stiffness of the pile, and
E_s = soil reaction modulus.

This well-known approach involves some serious drawbacks. The most noticeable one is that E_s is not a soil parameter but also depends intrinsically on the geometry and flexural rigidity of the piles as well as the boundary conditions (*5*). However, the method remains popular because of its simplicity and its capability to handle nonlinear *p-y* relationships. Case histories and methods of using laboratory and/or in situ test results to estimate the necessary soil *p-y* relationships have been reported by many authors [e.g., Briaud et al. (*6*); Gazioglu and O'Neill (*7*); and Robertson et al. (*8*)]. Commonly used in situ test methods include pressuremeter (PMT), field vane (FVT), and plate load tests. The use of flat dilatometer test (DMT) results in analyzing laterally loaded piles is relatively new. Regardless of methods used in the reported cases, they all have the drawback of being highly empirical. Also, only limited information is available as to the relative performance of each method. In fact, there appears to be a general lack of available data on small-diameter shafts founded within a desiccated clay crust.

The project reported herein concentrates on the behavior of small-diameter drilled shafts founded in a stiff clay crust and subjected to lateral loads. Foundations of this type are often used for structures such as guiderail poles, light poles, and transmission towers, where the foundation load in the axial direction is low compared to potential loads in the lateral direction. The relatively low cost and widespread location of these structures often do not justify elaborate subsurface explorations and analyses for each structural unit in the design of the foundations. In situ tests offer potentially cost-effective ways of providing the parameters necessary for valid analyses of such foundations.

In addition to laboratory tests, piezocone (CPTU), field vane, flat dilatometer, and pressuremeter tests were performed at the test site. Four concrete drilled shafts were installed. Table 1 shows the dimensions of these shafts. Results from FVT, PMT, and DMT were used to establish the necessary *p-y* relationships and predict the lateral response of the piles using a finite difference program. All predictions were made before the lateral load tests. The paper describes the details of these analyses and presents a discussion of the efficacy of the methods utilized.

SOIL CONDITIONS AT THE TEST SITE

The test site is located on Barnhart Island about 1 km north of the Snell Lock along the Saint Lawrence Seaway Canal, north of the village of Massena, New York. Field and laboratory investigations conducted at the test site indicate that the soils generally consist of Champlain Sea marine sediments, which occur throughout the Saint Lawrence Lowlands. The upper 2 to 3 m consists of highly overconsolidated and often fissured clays, as indicated by the results of CPTU (Figure 1) and FVT (Figure 2). Beneath this desiccated crust, the marine

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TABLE 1 DIMENSIONS OF THE DRILLED SHAFTS

Case	Diameter (cm)	Length (cm)
I	15.2	152
II	15.2	304
III	30.5	152
IV	30.5	304

clays are softer, slightly overconsolidated, and often sensitive. A summary of the soil conditions and a piezocone profile at the site are presented in Figure 1.

The upper 1 m of soil at the site is highly variable and contains abundant small sand lenses. Below this, the materials are more uniform and are generally classified as CH-CL according to the Unified Soil Classification System. Figure 2 presents the results of field vane tests along with other shear

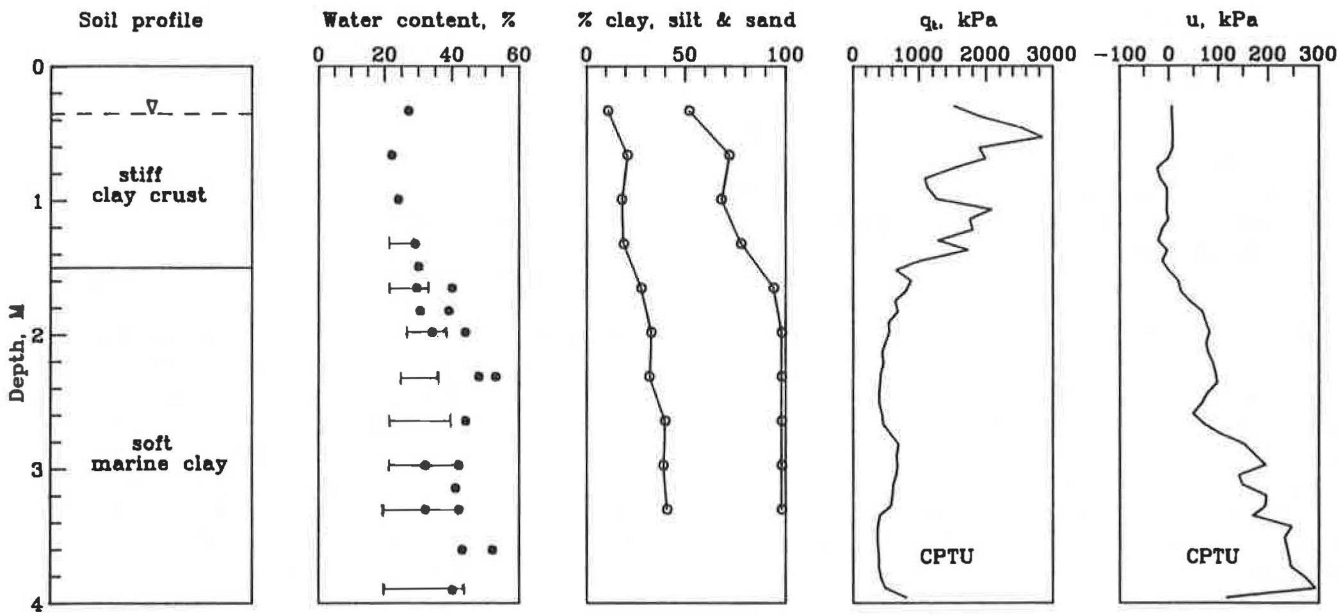

FIGURE 1 Soil profile at the test site.

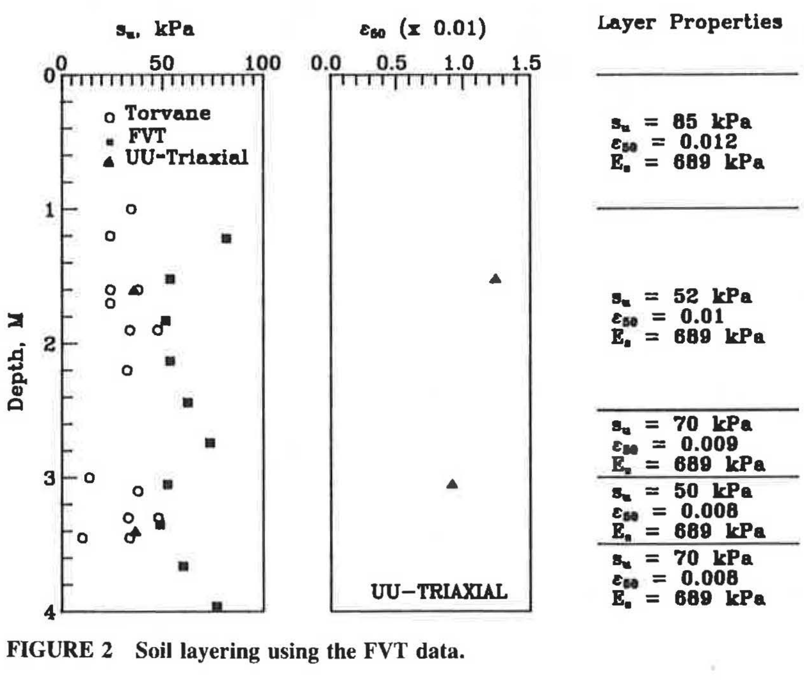

FIGURE 2 Soil layering using the FVT data.

strength measurements. These results are typical of marine deposits in the area.

PREDICTING LATERAL LOAD RESPONSE

The Numerical Technique

A finite difference program was written to solve Equation 1. The technique follows that of Reese and Allen (*4*). The pile is divided into segments such that the flexural stiffness (EI) and a nonlinear *p-y* relationship or the so-called *p-y* curve can be defined for each segment. The program is capable of handling general loading conditions at the shaft top that include axial load (P_x), bending moment, and lateral load. Zero moment and axial load were applied at the shaft top in all computations included herein, as they were the conditions applied in the field load tests. The following sections describe the details of constructing *p-y* curves using results from each of the three in situ test methods and predictions of the lateral load response for the drilled shafts.

Field Vane Tests (FVTs)

Reese and Allen (*4*) recommended that for submerged clays, the *p-y* curves be established based on a profile of undrained shear strength (s_u) and ε_{50}, the axial strain at 50 percent of the peak principal stress difference in a triaxial compression test. For soft clay soils that are normally or lightly overconsolidated, Matlock (*9*) recommended the FVT as the preferable method to determine the in situ undrained shear strength. Although this is not exactly the case for the clay crust, undrained shear strengths from FVT were used in establishing the *p-y* curves. This is primarily due to the lack of good-quality samples for laboratory testing, as is usually the case for clay crusts.

The *p-y* relationships were established according to the "integrated clay method" proposed by Gazioglu and O'Neill (*7*). This semiempirical method considers the effects of soil ductility, nonlinear dependence on pile diameter, and relative stiffness of soil and pile. It is applicable to both soft and stiff clays, as the name implies. A critical pile length (L_c) is computed first as

$$L_c = 3(EI/E_s D^{0.5})^{0.286} \quad (3)$$

where

D = diameter of the pile,
EI = flexural stiffness of the pile, and
E_s = average soil modulus.

The lateral load-deflection relationships are unaffected by penetration beyond L_c according to Gazioglu and O'Neill (7). The critical depth (x_{cr}) is related to L_c by the following equation:

$$x_{cr} = L_c/4 \quad (4)$$

A reference deflection (y_c) is defined as follows:

$$y_c = 0.8\varepsilon_{50} D^{0.5}(EI/E_s)^{0.125} \quad (5)$$

The ultimate soil resistance (p_u) is determined by

$$p_u = 0.75 N_p s_u D \quad (6)$$

and

$$N_p = 3 + 6(x/x_{cr}) \leq 9 \quad (7)$$

where x is the depth below ground surface. The lateral reaction (p) at depth x is then computed as

$$p = 0.5(y/y_c)^{0.387} p_u \quad (8)$$

Figure 2 shows the layering of the soil profile and parameters used in establishing the *p-y* curves and Figure 3 shows the typical shape of a *p-y* curve established on the basis of this method.

Pressuremeter Tests (PMTs)

Because of its lateral expansion, the pressuremeter provides a close simulation of a laterally loaded drilled shaft. At least seven methods (*6*) have been proposed to derive the *p-y* relationships and select the critical depths. Some of these methods are also applicable to self-boring pressuremeter tests. Full-displacement pressuremeter tests have been used to evaluate laterally loaded driven piles (*8*). Because only drilled shafts are involved herein, the *p-y* curves were established on the basis of a series of prebored, three-cell Ménard pressuremeter tests following the procedures recommended by Baguelin et al. (*10*). PMTs were conducted in hand-augered holes of 76-mm nominal diameter. Because of the size of the pressuremeter probe, it was necessary to perform tests at alternate depths in two adjacent boreholes.

This method considers the effects of pile dimensions and derives the subgrade reaction modulus (k) using the pressuremeter modulus (E_M), the pressuremeter creep pressure (p_f), and the limit pressure (p_l), as shown in Figure 4 and the following equation:

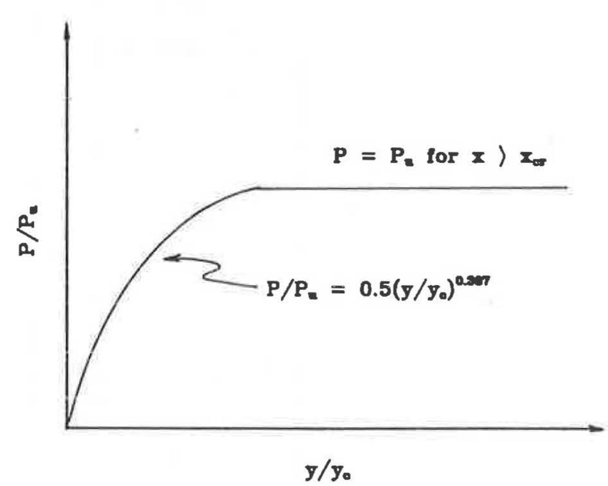

FIGURE 3 The *p-y* curve using the "integrated clay method."

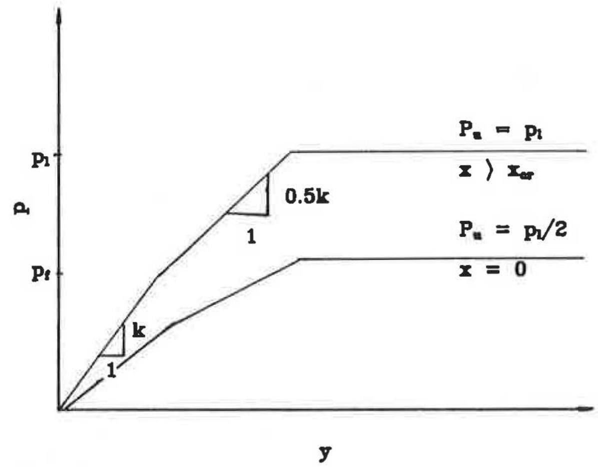

FIGURE 4 The *p-y* curve using the PMT method.

$$\frac{1}{k} = \frac{1}{9E_M}\left[2D_o\left(\lambda_d \frac{D}{D_o}\right)^{\alpha} + \alpha\lambda_c D\right] \tag{9}$$

where

E_M = pressuremeter modulus,
λ_d, λ_c = shape factors that depend on the length-to-diameter ratio of the pile,
α = rheological factor that depends on soil type and stress history (for overconsolidated clays, $\alpha = 1$), and
D_o = 60 cm as a reference diameter.

Values of λ_d and λ_c have been proposed by Baguelin et al. (*10*) for foundations with different geometries. A critical depth (x_{cr}) equivalent to twice the pile diameter was used, as suggested by Baguelin et al. (*10*). Values of k and p_l above the critical depth (Figure 4) are adjusted according to a reduction factor (λ_z), calculated as follows:

$$\lambda_z = (1 + x/x_{cr})/2 \tag{10}$$

On the basis of the results of PMTs, the soil was divided into three layers for analysis, as shown in Figure 5. The *p-y* relationships were then determined for each layer.

Flat Dilatometer Tests (DMTs)

The use of the DMT in analyzing laterally loaded piles is relatively new, and only a few cases have been reported (*5,11,12*). The potential advantages of using the DMT for this situation include:

- During the DMT membrane expansion, the soil is stressed in the lateral direction.
- Because of the small size of the instrument, the DMT is capable of providing soil modulus values at much closer intervals than are normally obtained with a pressuremeter; therefore, more detailed analyses that account for soil layering can be made. Typically, DMT tests are conducted at 0.3-m intervals, as was the case herein.
- The results of the DMT are more reproducible than those of the PMT, since the DMT does not involve different methods of inserting the probe (e.g., use of auger, self-boring pressuremeter, or Shelby tube) and is therefore much less operator-dependent.

Although the value of the DMT modulus (E_D) is obtained after full displacement of the soil resulting from inserting the blade, Lutenegger (*11*) has indicated that E_D is slightly higher than but close to the pre-bored PMT modulus (E_M), at least for the marine clays tested in the Massena area. Also, the

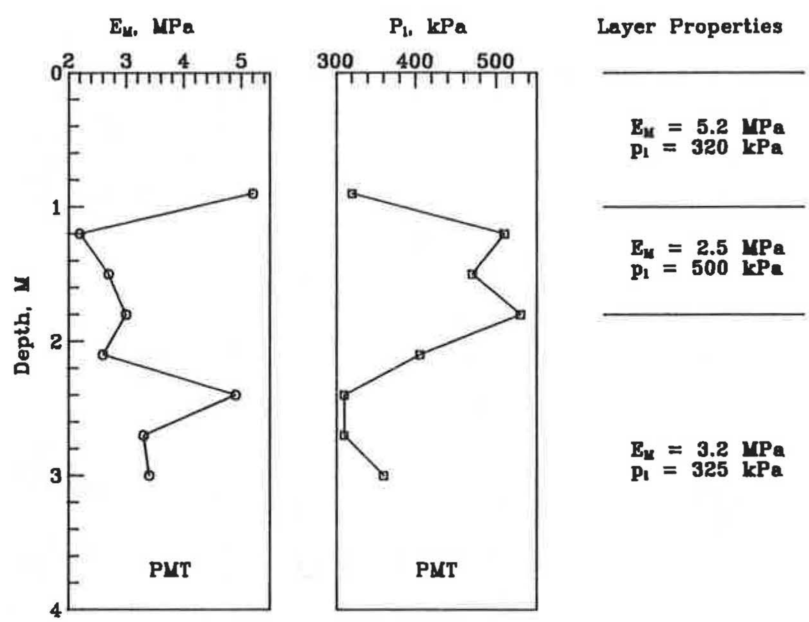

FIGURE 5 Soil layering using the PMT data.

PMT limit pressure (p_l) is approximately equivalent to the average of the DMT lift-off pressure P_0 and the 1-mm expansion pressure (P_1), i.e., $0.5(P_0 + P_1)$. Because of these similarities and for the sake of simplicity, it was decided to adopt the PMT method as described above in using the DMT data for the analyses. Therefore, modifying Equation 9 results in

$$\frac{1}{k} = \frac{1}{9E_D}\left[2D_o\left(\lambda_d\frac{D}{D_o}\right)^{\alpha} + \alpha\lambda_c D\right] \tag{11}$$

and the PMT limit pressure (p_l) is replaced with $0.5(P_0 + P_1)$. Figure 6 shows the results of the DMT tests and layering of the soil and parameters used in establishing the *p-y* curves. As mentioned previously, the DMT provides data with a much higher resolution, and this is reflected in the more detailed layering of the soil profile indicated.

The use of subgrade reaction modulus as proposed by Gabr and Borden (*12*) is another possible method of using the DMT for the analyses. However, it requires knowing in situ horizontal stress and therefore may be very subjective, especially in clay crust.

RESULTS AND COMPARISON

Field Load Tests

Four small-diameter drilled shafts (see Table 1 for dimensions) were installed at the site and allowed to cure for 30 days before load tests were conducted. Holes were drilled with a truck-mounted drill rig using continuous-flight augers and were filled with concrete immediately after drilling. Four No. 4 rebars were placed concentrically throughout the full length in each shaft. Concrete cylinders were taken during casting, and compression tests on these cylinders were conducted on the same day as the load test. The compressive strength of the concrete cylinders had an average value of 22 800 kPa. The lateral load tests were performed in close conformance with ASTM Standard D3966. Lateral loads were applied at the ground surface ($x = 0$), and two shafts were tested simultaneously by placing the hydraulic cylinder and load cell between them. Each load increment was maintained for 10 minutes. Free rotation was allowed at the shaft head at the ground surface.

Predictions

Qualitatively, all methods predicted similar patterns in deflection and soil reaction, as well as bending moment. As an example, Figure 7 shows the predicted deflection profiles of the shafts in all four cases (Table 1) according to the numerical analyses using results from the DMT, as the lateral load on the pile head varied from 2 to 20 kN. Except in Case II, the deflection of shafts was close to a rigid body rotation. Figure 8 shows the distribution of soil lateral reaction (force per unit length of shaft) according to results from the DMT, as the lateral load reached 10 kN. For the longer shafts (Cases II and IV), the soil lateral reaction from below the clay crust was rather insignificant. Figure 9 shows the predicted responses of the shaft for Case IV under a lateral load of 10 kN based on the three in situ test methods. It is clear that the added length of shafts in Cases II and IV did not cause any significant increase of lateral resistance due to the much softer soil conditions at the lower level.

Quantitatively, however, predictions from different methods are significantly different. For example, the displacement at the ground surface predicted by the PMT was 100 percent larger than that predicted by DMT. A discussion on the possible reasons for these discrepancies will be presented later.

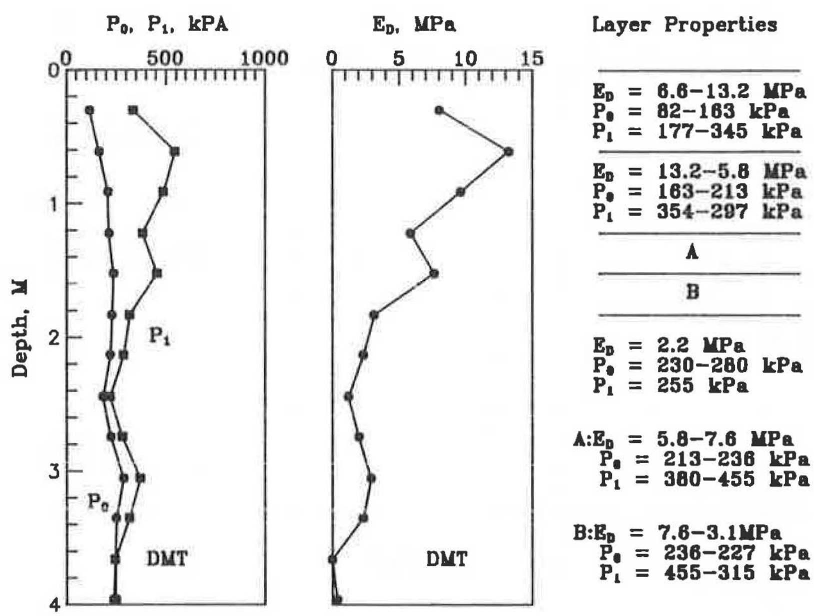

FIGURE 6 Soil layering using the DMT data.

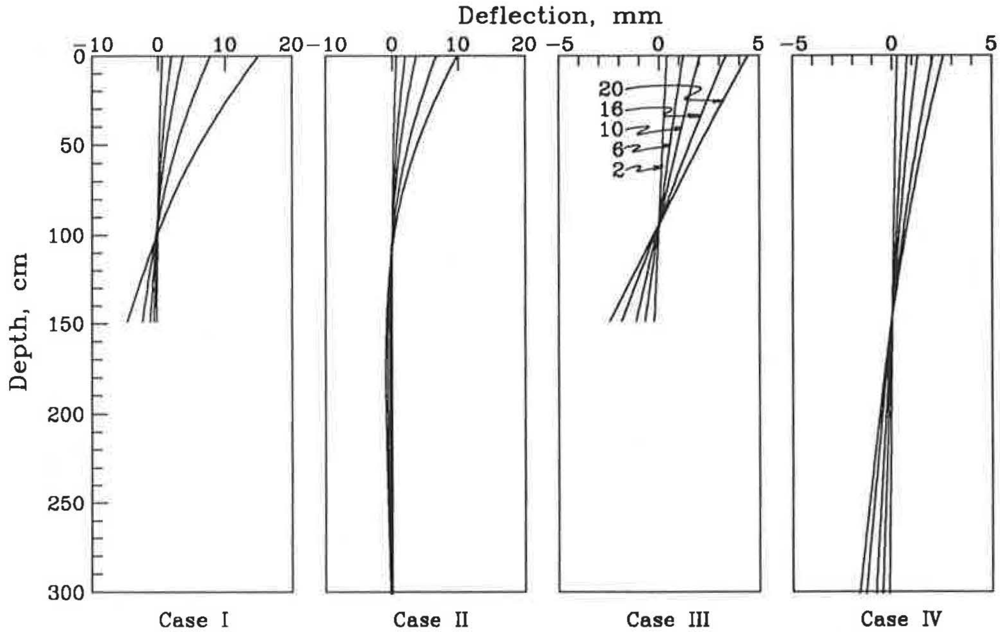

FIGURE 7 The predicted shaft deflection profiles.

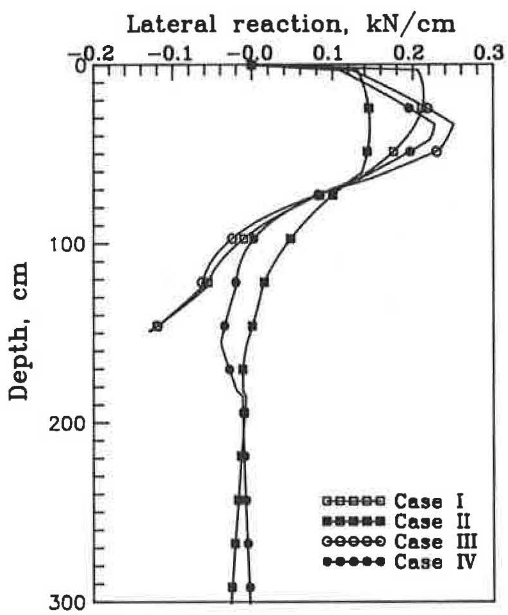

FIGURE 8 The predicted soil lateral reaction.

Comparison

Figures 10 and 11 show the predicted and measured displacement versus lateral load for all four cases. In all the field loading tests, the longer shafts (Cases II and IV) had more displacements than the shorter ones (Cases I and III). This contradicts all the predictions. One possible explanation is that there was more soil disturbance during drilling for longer shafts. The softening caused by disturbance might have offset the limited additional resistance from the extra length below a depth of 150 cm where the soil stiffness was much lower, as previously described.

The analytical solutions employed do have some built-in scale effects, e.g., critical depths, ignoring the influence of pile characteristics on the *p-y* curves, etc. The results did show that as the shaft diameter doubled in Cases III and IV, much closer predictions were obtained, as shown in Figure 11.

CONCLUSIONS

The determination of the engineering properties (i.e., strength and modulus) of desiccated clay crust is a difficult and challenging task. The use of in situ tests is attractive, as it is essentially impossible to obtain good-quality samples for laboratory testing (*13*). Studies by Bauer and Tanaka (*14*) indicate that in addition to the variable and fissured nature of desiccated clays, the interpreted undrained shear strength and modulus are very sensitive to different in situ test methods. They further suggest that a larger number of in situ tests is required to characterize the soil properties and to obtain statistically meaningful average values.

In establishing the *p-y* curves, there are significant differences in selecting the critical depths and subgrade reaction moduli among the available methods that involve in situ tests. These discrepancies are accentuated by the variable nature of the clay crust at the test site. No data in this study suggest that any one in situ test method is consistently better than the others in predicting the performance of this class of laterally loaded drilled shafts. It appears that the procedures for analyzing laterally loaded drilled shafts are limited in their usefulness in their present form for the unique combination of small shaft diameters and shaft location in a clay crust with somewhat variable properties. Further studies are warranted specifically for drilled shafts installed in clay crust. The improved

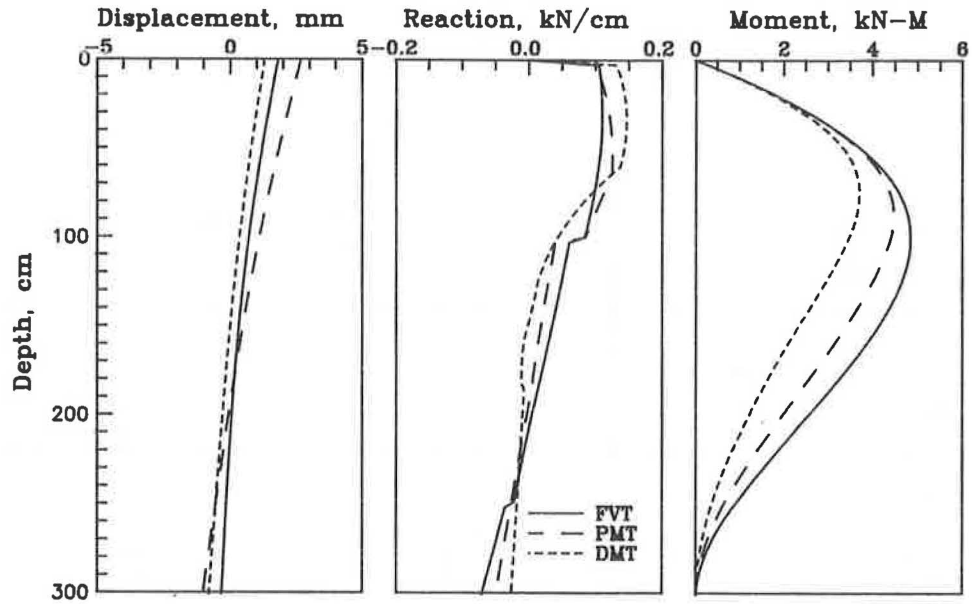

FIGURE 9 Predicted responses from different methods.

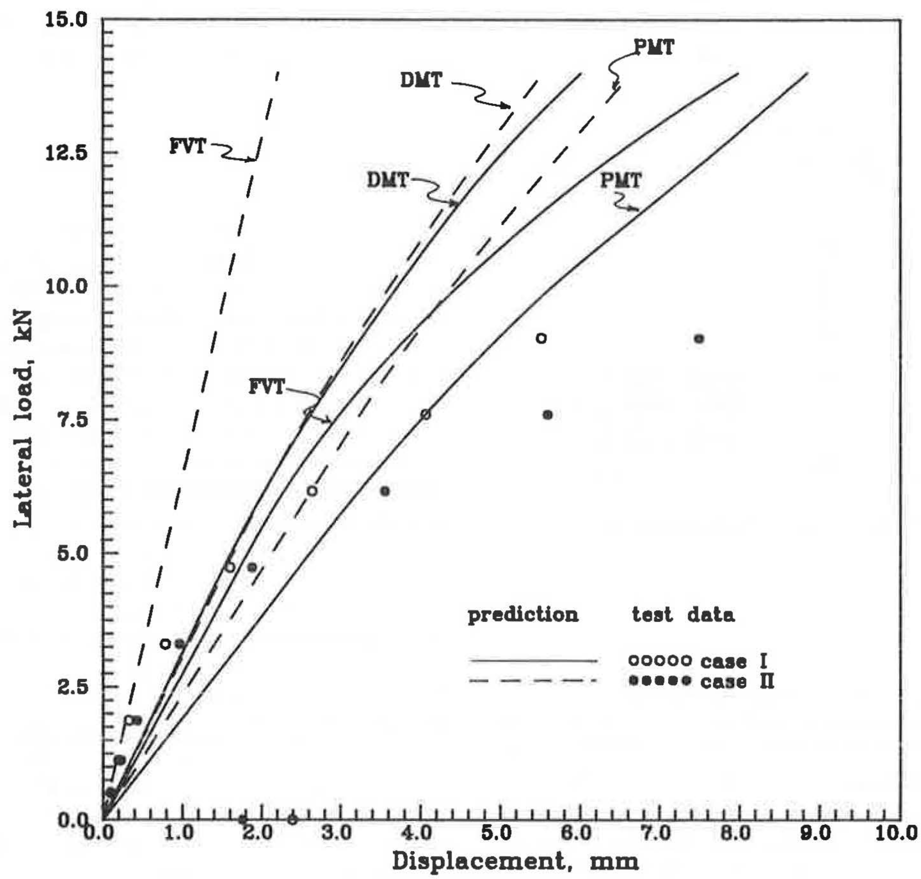

FIGURE 10 Predicted and measured displacement for Cases I and II.

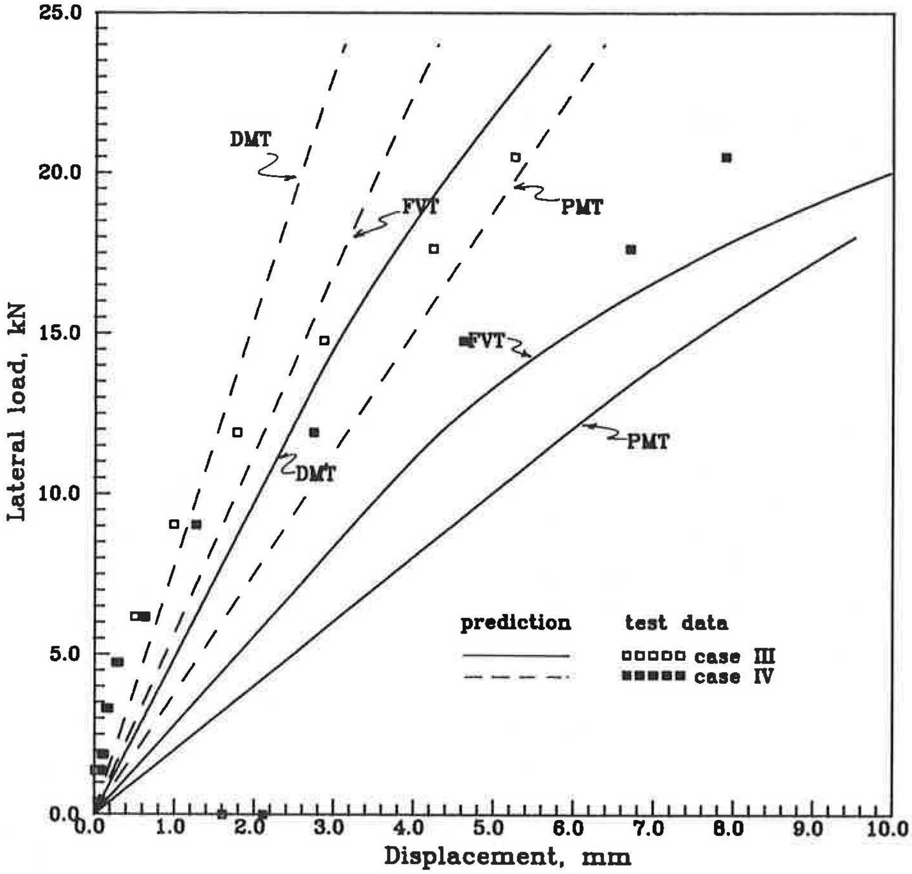

FIGURE 11 Predicted and measured displacement for Cases III and IV.

procedure should consider the scale effects of the small-diameter shafts and the existence of fissures.

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