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SYNOPSIS Results of lateral load tests on four drilled shafts installed in stiff cohesive soil are presented. Predictions of the load/displacement behavior were made using p-y curves generated from the results of Prebored Pressuremeter and Dilatometer Tests. A new method to develop p-y curves from the DMT is presented and discussed.

INTRODUCTION

The design of drilled shafts to sustain static one-way lateral loads is a common problem encountered in geotechnical engineering. A number of papers present the results of studies conducted to evaluate the performance of rigid drilled shafts under lateral loads, (e.g., Adams and Radhakrishna, 1973; Reese and Welch, 1975; Ismael and Klym, 1978; Bhushan et al., 1979; Vallabhan and Alikhanlou, 1982; Coyle and Bierschwale, 1983). In the last ten years, considerable attention has been given to this problem and to the application of in situ tests to provide soil parameters for input. Design methods making use of both the prebored pressuremeter, PMT, and the flat dilatometer, DMT, have been presented as appropriate techniques for drilled shafts in clays and sands (e.g., Briaud et al., 1983, 1984a, 1984b; Gabr and Borden, 1988; Borden and Lawter, 1989; Huang et al., 1989). These tests may be performed rapidly and with relative ease and are therefore attractive for an economic approach to design.

In this paper, a comparison is made between the results of lateral load tests conducted on four drilled shafts and predictions of load/displacement curves made using the results of both prebored pressuremeter and dilatometer tests. An approach is presented using the dilatometer to develop the full p-y curve for use in design.

TEST PROGRAM

Test Site

Tests were performed at a permanent research site located on the University of Massachusetts campus in Amherst, Massachusetts. The site is situated in the Connecticut River Valley of Western Massachusetts and consists of approximately 1 m of compacted, mixed cohesive and cohesionless fill over a relatively thick (25 m) deposit of lacustrine varved clay. The upper 8 to 10 m of varved clay is overconsolidated as a result of overburden erosion, chemical weathering and fluctuations in the water table. The water table at the site varies on the order of 1 to 2 m seasonally and generally occurs on average at a depth of about 2 m below the ground surface. A summary of the site geotechnical characteristics in the upper 5 m is presented in Figure 1.

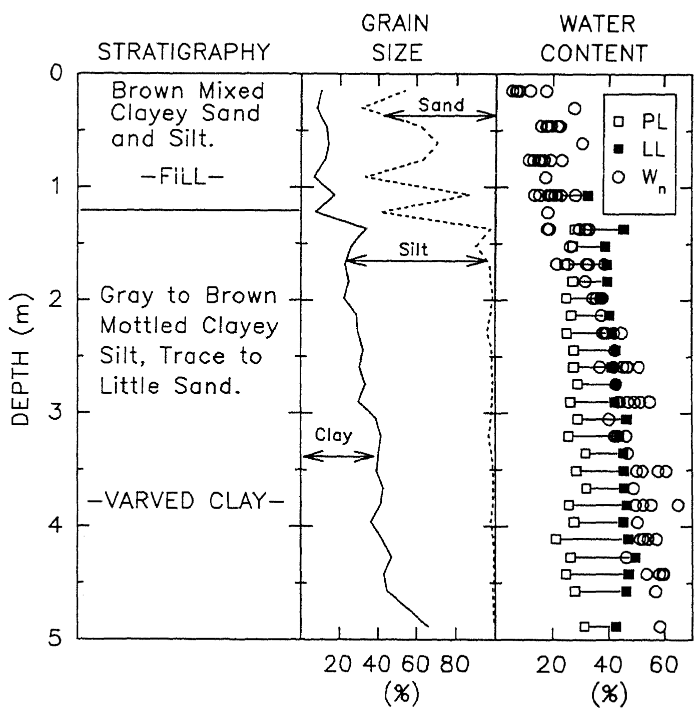

Figure 1. Soil Characteristics

In Situ Tests

In situ tests performed at the site for use in the predictions of drilled shaft behavior included prebored pressuremeter and flat dilatometer tests. To obtain vertical profiles of the soil response, tests were conducted every 0.3 m over the length of shaft embeddment starting at 0.6 m and 0.3 m below the ground surface, for the PMT and DMT, respectively.

Pressuremeter tests were conducted using an NX size (76 mm) monocell pressuremeter with a nominal length/diameter ratio of 6.4. Holes were drilled using a 76 mm diameter bucket-type hand auger which caused minimal disturbance to the side walls. Measurements of cavity deflection were made using strain gaged feeler arms which tracked the inside of the probe membrane during expansion. Probe inflation was accomplished using nitrogen. Testing procedures generally followed the outline presented in ASTM D 4719.

Flat dilatometer tests were conducted following the procedure described by Schmertmann (1988).

Installation of Drilled Shafts

All four shafts were installed using a single flight helical auger. Holes were dry upon completion of drilling and prior to placement of concrete. Steel reinforcing cages, consisting of four #6 rebars and #4 rebar square ties, were installed in the holes and concrete was placed by gravity free fall. Characteristics of the shafts and properties of the concrete are presented in Table 1.

Table 1. Shaft Characteristics

Shaft Number	Diameter, D (m)	Length, L (m)	L/D	f'_c (MPa)
1	.51	1.52	3.0	27.6
2	.51	2.44	4.8	27.6
3	.61	1.52	2.5	27.6
4	.61	2.44	4.0	27.6

Load Testing

Load tests were performed by applying a ground-line lateral force between pairs of shafts using a manually controlled hydraulic jack. An in-line load cell with a resolution of 0.07 kN was used to measure the load. Ground-line displacements at each shaft were measured using a dial gage with a resolution of 0.025 mm. Loads were applied in increments of approximately 5 to 7 % of the predicted ultimate capacity and were maintained for twenty minutes. Load tests were conducted approximately one year after installation of the shafts.

METHODS OF ANALYSIS

Method of Solution

To obtain predictions of the ground line deflections of the shafts, a finite-difference approximation to the governing fourth order differential equation was made. The governing differential equation takes the form:

$$EI(d^4y/dx^4) + q(d^2y/dx^2) - p - w = 0 \quad (1)$$

where: q = axial load on the shaft,
y = lateral deflection at point x along the shaft,
p = soil reaction per unit length,
EI = flexural rigidity, and
w = distributed load along the shaft length.

The computer program used, LPILE1, is commercially available from Ensoft, Inc., and was developed by Lymon C. Reese. The program is equipped with subroutines to generate p-y curves from soil properties and also allows the user to input p-y curves. For predictions made in this paper, p-y curves were developed using test results from the PMT and DMT, as discussed subsequently.

Pressuremeter

Individual pressuremeter tests were used to develop p-y curves on 0.3 m intervals along the shafts, starting at a depth of 0.6 m. The method used to derive the p-y curve from the pressuremeter expansion curve is known as the Briaud-Smith-Meyer method (Briaud et al. 1983). This method is a compilation of observation and theory. It operates on the premise that the p-y curve is the sum of the front reaction, Q-y, curve and the side or friction reaction, F-y, curve. Pressure cell measurements on the front of a laterally loaded shaft indicated that the side friction can be an important component of the total resistance (Smith and Ray, 1986). It was also found that the pressure cell measurements closely matched the pressuremeter response in the same soil. Thus, the pressuremeter curve may be used directly to obtain the Q-y curve. The F-y curve is slightly more elusive and requires a good deal of engineering judgement. Baguelin et al. (1978) derived soil shear stress-strain curves from self-boring pressuremeter curves using the subtangent method of analysis. Smith and Ray (1986) found that applying this same method to the reload cycle of pre-bored pressuremeter tests provides results comparable to self-boring test.

In order to obtain appropriate p-y curves, reduction factors must be applied to the Q-y and F-y curves to account for the critical depth of the pressuremeter and/or shaft (Briaud et al., 1984). In addition, a reduction may need to be applied to account for the difference in the level of disturbance that occurs between a pressuremeter test hole and a drilled shaft excavation. Uplift tests on drilled shafts constructed using different augering techniques at the UMASS Test Site indicate that a 50 % reduction in the mobilized shear stress occurs as a result of mechanical flight augering as compared to hand augering. For this reason, in this study the F-y curves were adjusted accordingly.

Dilatometer

The dilatometer was used to provide p-y curves at 0.3 m intervals along each shaft. Methods exist which incorporate the DMT geometry and membrane lift off pressure, P_0, to obtain a subgrade reaction modulus, k, which is then substituted into a function to generate the p-y curve (Gabr and Borden, 1988; Schmertmann, 1988). In some instances a correction factor is applied to account for size effects. Common to all of these methods is the need to approximate the ultimate resistance of the soil, p_u. Thus, at a minimum these methods usually require an estimate of shear strength parameters, horizontal earth pressure coefficient, vertical effective stress and various empirical factors used in the approximation of p_u.

A goal of this study was to initiate the development of a DMT method for p-y curve generation which incorporates primarily the DMT measurements. The goal was to minimize the reliance on soil parameters determined by other testing or empirical methods while maintaining a satisfactory level of performance. Specifically it was felt that P_0 and the 1 mm expansion pressure, P_1, could be used to construct a p-y curve. This opinion was formed partly on the basis of observations made by Lutenegger and Blanchard (1990), who showed that the DMT P_1 pressure corresponds very closely to the limit pressure, P_L, from full displacement pressuremeter tests. Since the value of P_L represents a limiting soil resistance, a good first approximation of p_u should incorporate P_1. In order to obtain an approximation of p_u, P_1 must first be multiplied by the shaft diameter to obtain the appropriate units of force/length. Additionally, Schmertmann (1988) suggested that for a reference width of 0.3 m, the subgrade reaction modulus is about one half of that determined with the DMT. For widths greater than 0.3 m it may be appropriate to apply a size correction factor such as that suggested by Terzaghi (1955). Although, the proposed method does not incorporate a direct estimate of subgrade reaction modulus, it was felt that the size correction factor may be applicable because the slope of the p-y curve is proportional to the subgrade reaction modulus (i.e., slope/shaft diameter = k). Other methods which utilize the DMT k value to develop the p-y relationship have implicitly applied this correction factor (when it is used) to all values of p on the curve. The resulting equation for p_u takes the form:

$$p_u = P_1 \times D \times CF \qquad (2)$$

where: CF = size correction factor

$= 0.5[(D + 1)/(2D)]^2$, and

D = shaft diameter.

Having established p_u, the next step is to determine the appropriate function to develop the p-y curve. The curve fitting method selected was that proposed by Gazioglu and O'Neill (1984) in their "integrated clay method" where the p-y curve function is:

$$p/p_u = 0.5(y/y_c)^{0.387} \qquad (3)$$

where: y_c = reference deflection.

To establish an appropriate p-y curve, the reference deflection, y_c, must first be determined and takes the following form:

$$y_c = 0.8\epsilon_{50}D^{0.5}(EI/E_s)^{0.125} \qquad (4)$$

where: ϵ_{50} = 50 % axial strain from a triaxial compression test, and

E_s = average soil modulus.

From this equation, it can be seen that y_c is relatively insensitive to E_s and for this reason the dilatometer modulus E_D can be used as a reasonable estimate of E_s. E_D is simply a function of the DMT expansion kinematics and the P_0 and P_1 pressures. An estimate of ϵ_{50} is needed to determine an appropriate y_c. Unfortunately, this is where the proposed method relies on an externally determined soil parameter, however, this parameter has been well established for a variety of soil types and can be routinely determined in the lab. For the purpose of this study a value of 0.007 was used. It should be noted that the larger the value of ϵ_{50}, the more conservative the predictions will be.

From Equation 3 it can be seen that the value of p_u occurs when $(y/y_c) = 6$ as shown in Figure 2. Beyond this point the value of p/p_u is generally assumed to be constant. However, it was found in this study that the predictions at larger shaft displacements were slightly better when the parabolic equation was used for $(y/y_c) > 6$.

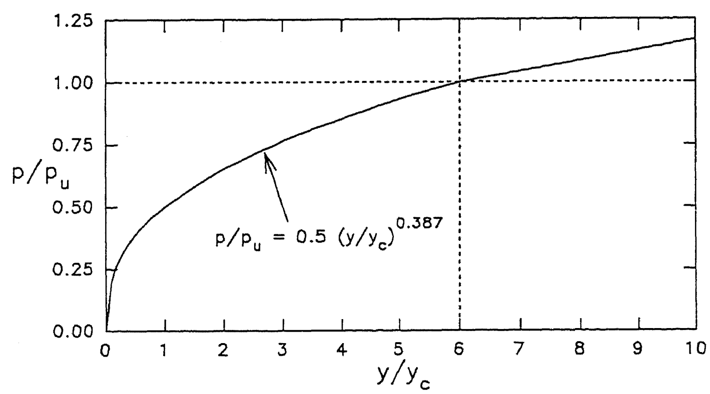

Figure 2. DMT p-y Curve

RESULTS AND DISCUSSION

Comparison of the predicted and measured response of the four laterally loaded shafts is presented in Figure 3. The measured response for the shafts does not reflect the small size difference between the two diameters used. In fact the longer 0.51 m diameter shaft showed a stiffer response than the 0.61 m diameter shaft of the same length. This may be partially attributed to the natural variability of the surficial soil.

Predictions based on both the PMT and the DMT show essentially the same load/displacement curves for shafts of the same length and different diameters. The shape of the load/displacement curves predicted by the DMT more closely matches the shape of the actual curves as compared to the PMT, for shafts 1, 3 and 4. The poorer match displayed for Shaft 2 may simply be due to the fact that this shaft, contrary to that expected, exhibits stiffer behavior relative to the larger shaft of the same length.

Currently, the proposed DMT method is in the initial stage of development and further investigation of its appropriateness for other shaft geometries and soil types is required. At the present time it appears to be a promising approach and additional effort is being given to this method.

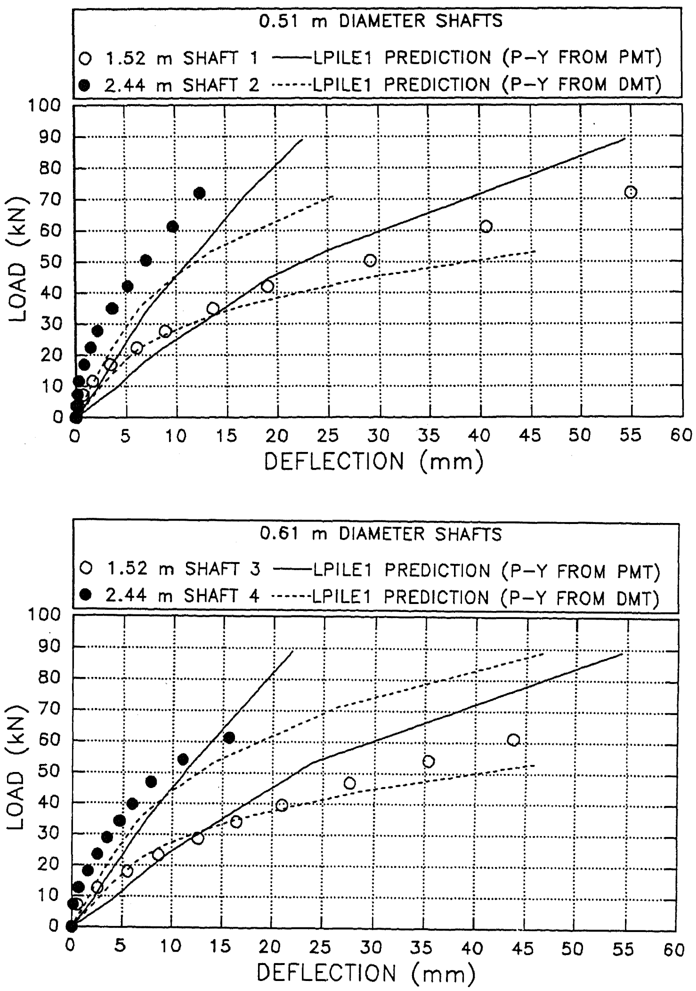

Figure 3. Shaft Load/Displacement Curves

LIST OF SYMBOLS

CF = size correction factor
D = shaft diameter
E = shaft modulus of elasticity
E_D = DMT modulus
E_s = soil modulus of elasticity
ϵ_{50} = 50 % axial strain from a triaxial compression test
f'_c = concrete compressive strength
F = friction component of soil reaction, p
I = moment of inertia
k = soil subgrade reaction modulus
L = shaft length
LL = liquid limit
p = soil reaction per unit length of shaft
P_0 = DMT lift off pressure
P_1 = DMT 1 mm expansion pressure
P_L = PMT limit pressure
PL = plastic limit
p_u = ultimate lateral soil resistance
Q = normal component of soil reaction, p
q = axial load on the shaft
w = distributed load along the shaft length
W_n = natural water content
y = lateral displacement along the shaft
y_c = reference deflection

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