Directors' research and development activities

Analysis of load-settlement behavior in bi-directional static load tests of bored piles

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Abstract

The presence of soft-toe conditions is a common problem of cast-in-place bored piles. This paper describes a modified method for obtaining the equivalent pile head load-settlement curve from the results of bi-directional pile load tests. The modified method considers soft-toe conditions in which the load-displacement along the side and toe of the pile are estimated using cubic-spline interpolation in place of the traditional hyperbolic approximation. The proposed method is applied to test data obtained from BDT data to illustrate the method and compare the resulting equivalent pile-head load-settlement obtained from the conventional method of analysis.

I. Introduction

Cast-in-place bored pile foundations are a commonly used foundation scheme in the Philippines. Bored pile foundations offer several advantages over pre-cast reinforced concrete pile foundations: less vibration and potential for damage to adjacent structures, less wastage because piles are cast to the required length, and greater capacity to resist large lateral loads and bending moments. Bored piles tend to be larger in diameter, carry larger loads, and are often more expensive when compared to driven piles with similar axial capacity. Bored piles generally range in diameter from 0.8m to 3.6m, although the majority of bored piles constructed in the Philippines are between 1.0m to 1.2m in diameter.

Because bored piles are larger than driven piles, they generally carry larger loads. This allows a single bored pile to replace a group of driven piles and avoids pile-group interaction effects. However, the reduced redundancy has serious consequences since the failure of a single bored pile may be catastrophic. This emphasizes the need for proper pile testing to ensure that the pile has sufficient capacity to carry the design load within set displacement tolerances. In the Philippines, piles are tested using both the static load and the high-strain dynamic tests. In the conventional static pile load test, a load frame is supported on four reaction piles constructed so that the test pile is placed in the middle of the load frame. A hydraulically driven load cell is placed on the top of the test pile, which pushes down on the test pile. The test pile is instrumented with displacement transducers at the top of the pile to measure settlement at the top of the pile. From the results of the test, a load settlement plot is obtained from which the ultimate load can be estimated.

II. Bi-directional Static Load Test

An alternative to the conventional static load test is the bi-directional (BDT) test (ASTM D8169-18), in which a load cell is installed within the pile. The BDT test was first proposed and developed by Osterberg [1]. Since its inception, the Osterberg Load Cell test has undergone numerous modifications and improvements [2]. Fig. 1 shows a typical setup for a bi-directional static load test. The test involves the use of a load cell embedded into the pile. The load cell is ideally installed at the equilibrium point within the pile, which corresponds to the estimated point at which the ultimate side and end-bearing resistance are simultaneously reached during the loading of the cell. The equilibrium point is estimated based on the preliminary computations needed to estimate the pile capacity. Installation of the load involves first fabricating the rebar cage of the upper and lower segments of the pile separately and then welding the two segments together with the cell sandwiched between the two segments. Strain gauges can be attached to the rebar cage at selected locations in the upper segment of the pile allowing the variation in axial load to be estimated and these selected points to be estimated. In general, strain gauges at not installed below the Osterberg cell due to difficulties in passing wires from strain gauges to the data acquisition system at the ground surface through the load cell. The completed load cell is then placed in the pre-drilled shaft prior to concreting of the pile.

When compared to conventional top-loaded static pile load tests, BDT tests are safer, require less space to perform, and do not require reaction piles. Provided that the load cell is installed close to the equilibrium point, bi-directional loading enables the pile to be tested to double the load cell capacity. The most notable advantage of BDT is its ability to simultaneously monitor the load settlement behavior of the upper and lower segments of the pile separately.

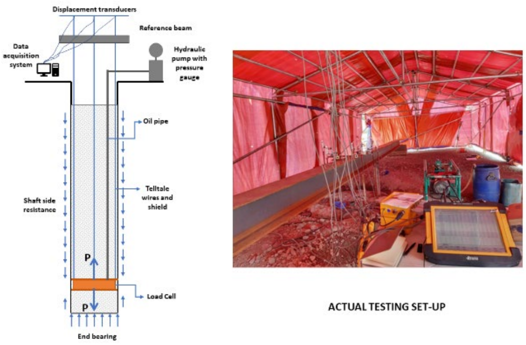


Fig. 1. Bidirectional test setup (from Gong et al. 1984 [4])

During testing, pressure in the load cell is measured by a manometer, and the displacement is measured by means of tell-tale rods and displacement transducers. Pressure to the load cell is applied by a high-pressure oil pump on the ground surface. During loading, the load cell expands, pushing the upper shaft upward and the lower shaft downward. The displacement resulting from resistance in the upper segment and the combined side and base resistance for the lower segment of the pile shaft are measured separately and result in two load-settlement curves for the upper segment and lower pile segment.

One of the challenges in interpreting results from the bi-directional pile load test is obtaining the equivalent load-settlement curve corresponding to a conventional top-loaded static pile load test. The pile head settlement in bi-directional static loading tests is calculated based on: (1) the side shear load-displacement curve, obtained from the upward movement of the top of the load cell, and (2) the end bearing load-displacement curve, obtained from the downward movement of the bottom of the load cell. The original method assumes that: the pile is a rigid body, the movements of the pile head and bottom are the same, and the upward skin friction is equal to the downward skin friction. The equivalent pile head settlement is obtained by adding the side friction to the end-bearing load at the same deflection. However, neglecting the portion of the elastic shortening of the pile results in an underestimation of the pile-head settlement when the load-displacement curve is computed using the original method. The magnitude of the underestimation increases with increasing pile length. In order to address this limitation in the original method, Fellenius et al. [3] used the finite element method to obtain the equivalent top-loaded load-settlement curve from BDT results.

It can be shown that bearing capacities and the factors of safety decrease when elastic compressions of the piles are considered. Gong et al. [4] proposed precise and approximate conversion methods based on the theory of elasticity. Lee and Park [5] proposed a simplified elastic method for constructing a realistic pile load-settlement curve. In the simplified elastic method, a shape factor dependent on skin friction distribution is assumed for calculating the elastic shortening of the piles. The proponents of this method present empirical evidence based on pile load tests to show that the equivalent load-settlement curve obtained from BDT results using the simplified elastic method is similar to those obtained from conventional top-loaded static pile tests. The following section describes the simplified elastic method.

III. Construction of the equivalent load settlement curve

This section describes the modified procedure involved in constructing the equivalent load settlement curve for the BDT assuming a deformable linear elastic pile as described in [5]. Derivation of the closed-form expressions for computing the elastic shortening of the pile, which are not included in [5], is first discussed, after which their use in constructing the equivalent load settlement curve is explained.

3.1 Bottom loaded pile

The elastic shortening of δ_0 of a pile with constant stiffness AE and length L subjected to an upward force Q_{net} applied to the bottom of the pile, and downward side resistance is given by the equation:

$$\delta_0 = (1 - c_1)\frac{Q_{net}L}{AE} \quad (1)$$

where the parameter c_1 depends on the distribution $f(z)$ of the side resistance along the length of the pile according to the equation:

$$Q_{net} = \int_0^L f(z)dz \quad c_1 = \int_0^L z\, f(z)dz / Q_{net} \quad (2)$$

The value of c_1 for each load step in the BDT is calculated from the elastic shortening δ_0 of the upper segment of the pile. In this case, the load Q_{net} represents the difference between the load Q applied by the load cell, and the buoyant weight W_b of the upper segment of the pile. It should be noted that the load cell must overcome W_b before the pile segment can displace upward. The elastic shortening at each load step of the test is determined from the displacement of the top of the load cell, corresponding to the bottom of the upper pile segment, and displacement at the top of the upper segment of the pile, which are routinely measured at each load. Consequently, the value of c_1 for each load $Q_{net} = Q - W_b$ can be computed only for values Q is greater than W_b.

3.2 Top loaded pile

The elastic shortening δ_L of a pile with constant stiffness AE and length L subjected to a downward force Q_T applied to the top of the pile at the ground surface, an upward force Q_b applied to the bottom of the pile, and an upward side resistance varying along the of the pile according to the function $f(z)$

$$\delta_T = c_1 \frac{Q_T L}{AE} + (1 - c_1) \frac{Q_b L}{AE} \tag{3}$$

The expression for δ_L as given in equation (3), is used to estimate the elastic shortening for both the lower pile segment of a BDTs and conventional top-loaded pile test, in which Q_T is the load applied at the top of the pile, $Q_b = Q_T - F$, and F is total side resistance.

3.3 Approximation load-settlement curves from bi-directional pile tests

In the original procedure developed by Osterberg [1], the load-settlement curves obtained from the bi-directional load test are separately approximated using the hyperbolic relationship proposed by Konder [5]:

$$P = \frac{u}{a + b\,u} \tag{4}$$

in which P is the load corresponding to a settlement u. The parameters a and b are parameters obtained by fitting the results of the Bi-directional pile load test into equation (4). Separate values of a and b are obtained for the upward and downward load-settlement curves, such that the end-bearing load Q_B and side resistance Q_s are approximated according to the following hyperbolic relationships:

$$Q_B(u) = \frac{u}{a_B + b_B u} \tag{5}$$

$$Q_s(u) = \frac{u}{a_s + b_s u} \tag{6}$$

Gross test loads are used in the regression analyses to determine the parameters a_B, b_B, a_s and b_s. Value of Q_S and Q_B are valid only for values of u within the range of the test data.

The first approximation to the load-settlement curve is obtained by solving for the top load corresponding to a given displacement u using equation (5) for the lower pile segment and equation (6) for the upper pile segment is given b:

$$Q_T(u) = Q_s(u) + Q_B(u) - W_b \tag{7}$$

Although equation (7) assumes that the pile behaves as a rigid body, some elastic compression due to Q_s is included in u. To correct this, the elastic compression δ_0 in a pile due to Q_s is computed using equation (7). Using $Q_T^*(u_1)$ and equation (3), the elastic compression δ_T in a top-loaded pile is computed and added to u_1 to give the settlement u_1^* corresponding to Q_T^*. The values of u_1^* and Q_T^* are plotted to give the load-settlement curve for the equivalent top-loaded pile. Although the specific distribution of skin friction $f(z)$ along the pile is not known. The coefficient c_1 can be computed from equation (1) using the BDT load-displacement data from the upper pile segment.

For cases involving bored piles with soft-toe conditions, the load-displacement curve may deviate significantly from a hyperbolic relationship depending on the extent of the soft-toe conditions. For such cases, the author suggests using cubic spline interpolation, which has the ability to represent more complex relationships. Cubic spline interpolation is a numerical method for fitting a curve through a given finite set of data points in a piecewise manner using third-order polynomials. The results curve is smooth and continuous until the second-order derivatives. For purposes of this study, cubic spline interpolation was performed using a subroutine function based on Press et al. [7]. The proposed method involves replacing Equations (5) and (6) with:

$$Q_B(u) = \Phi(u, \hat{u}_B, \hat{Q}_B) \quad (8)$$

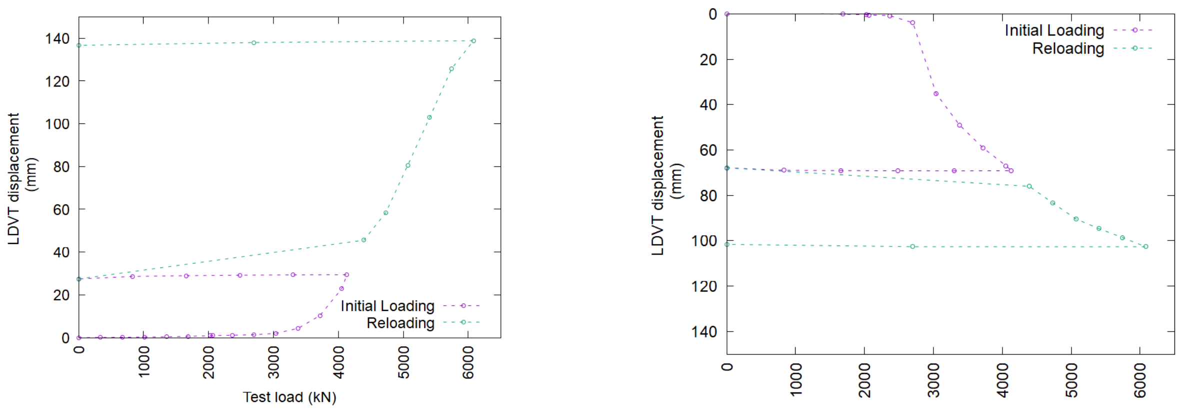
$$Q_s(u) = \Phi(u, \hat{u}_S, \hat{Q}_S) \quad (9)$$

where Φ is the cubic interpolation function $(\hat{u}_B, \hat{Q}_B)$ are the load-displacement data from the lower segment of the BDT, and $(\hat{u}_S, \hat{Q}_S)$ are the load-displacement data from the upper segment of the BDT. The remaining steps of the procedure remain the same.

IV. NSCR Project Test pile TP-3

The North-South Commuter Railway (NSCR) Project involves the construction of a 146-kilometer railway system in the Philippines connecting the National Capital Region with the provinces of Laguna in the south and Pampanga in the North. Since many parts of the railway system lie on sites underlain with soft clays and liquefiable sand, pile foundations are widely used in many structures in the system. This section describes the analysis of the BDT performed on a bored part within the NSCR System.

The test involved a 1.5 m diameter cast-in-place bored pile 36 m in length cast with concrete having a 21-day unconfined compression strength of 28 MPa. The maximum equivalent top-down test load was 13,516 kN. The load cell was placed 6.4 m above the pile toe. The load-settlement curve is shown in Fig. 2. The initial load cycle wherein the pile was loaded to twice the working load (8,264 kN), with measured maximum upwards and downwards load cell displacement of 29.4 mm and 69.15 mm, respectively. Unloading then followed, during which residual settlements of 27.45 mm and 67.9 mm were recorded after the complete removal of the test load. Then the pile was loaded to 8,786 kN (next higher load stage from 2 x Working Load) and then loaded in increments of 676 kN (5% of Target Max Test Load of 13,516 kN). Loading prematurely ended at the maximum test load of 12,614 kN with measured maximum upwards and downwards load cell displacement of 138.8 mm and 102.68 mm, respectively, as the upward load cell displacement was close to the maximum allowable stroke of 150.0 mm.



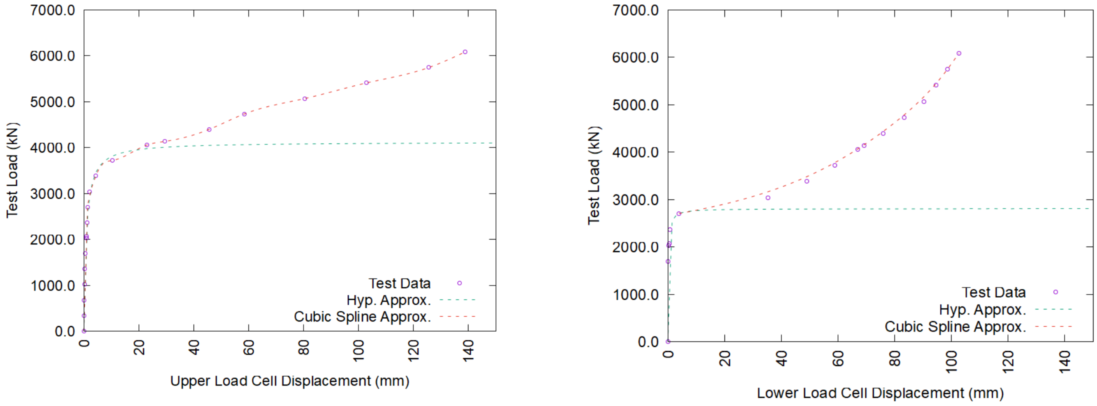
(a) Upper pile segment (b)Lower pile segment

Fig. 2. BDT results

Fig. 2b shows a change in curvature from concave downward to concave upward, starting at a gross load of 2703 kN during the initial loading stage. This is surmised to be due to the presence of soft toe conditions at the base of the test pile. During the initial stages of the initial loading, the soft toe condition resulted in significantly larger displacements in the lower segment of the pile compared to the upward segment. However, at higher loads during the reloading stage, the soft toe appears to attenuate, resulting in an increase in stiffness with increasing test load.

During the process of obtaining the equivalent top-loaded load-settlement plot, the upward and downward load-displacement plots were each initially fitted into a hyperbolic function using Equations (5) and (6) to obtain the equations that would relate the pile load and displacement. However, it was noted that for a given displacement, the hyperbolic approximation significantly underpredicted the equivalent load for both the upper and lower pile segments. To better model both the upward and downward load-displacement behavior based on the load test data, the load settlement curve was modeled using a cubic spline, and Equations (8) and (9) were used in the calculations for obtaining the equivalent top-loaded displacement-load curve.

The resulting hyperbolic and cubic spline curves are plotted versus the test data for the upper and lower pile segments in Fig. 3. It can be seen that the cubic spline curves, while not as smooth as the hyperbolic functions, result in a load-displacement curve that is much more faithful to the BDT load-displacement data.



(a) Upper pile segment (b) Lower pile segment

Fig. 3. Interpolated load-settlement for upper and lower pile segments

The calculated equivalent top-down load-settlement plot, both for the uncorrected and corrected pile's elastic shortening, is shown in Fig. 4 based on the procedure described in previous sections. Based on the analysis, it may be concluded that in the equivalent top-down load set plot, the pile set at twice the working load (2xWL = 8,264 kN) is estimated to be about 85.4 mm and only about 3.6 mm under working load (4,132 kN). The predicted pile set at the working load of 3.6 mm satisfies the design criterion of 12 mm at the working load. However, the predicted pile settlement of 85.4 mm does not meet the maximum allowable settlement of 38mm at twice the working load. It is also apparent that the predicted residual settlement at twice the working load will be greater than the maximum allowable value of 6.5 mm.

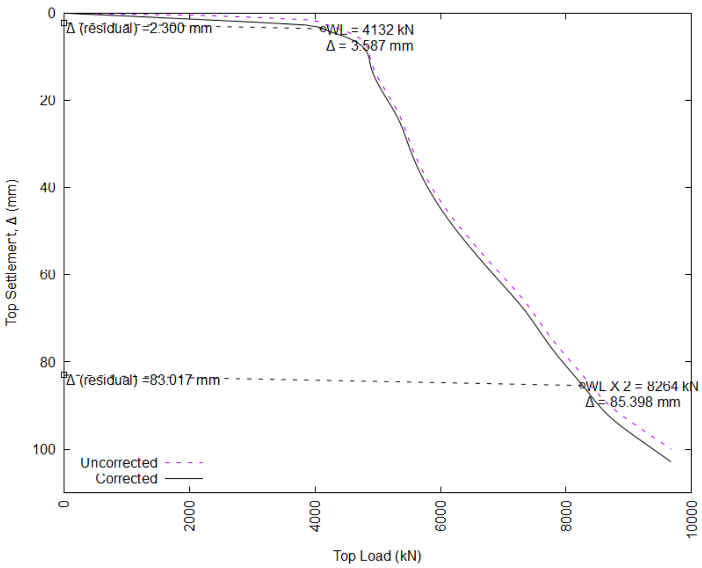


Fig. 4. Equivalent top-loaded load displacement curve

V. Conclusion

In the Philippines, the occurrence of soft toe conditions in bored piles is commonplace. For bi-directional pile load tests, the presence of soft toe conditions is manifested by large settlements for the lower segment of the pile. Experience indicates when a soft toe is present, the load-settlement behavior cannot be accurately modeled using the conventional hyperbolic function. The use of a hyperbolic function to estimate the load-settlement behavior often leads to an underprediction of the allowable pile capacity.

In such cases, it is proposed that the load-settlement curve be approximated from test results using cubic spline interpolation. It can be shown that despite the presence of soft toe conditions, side resistance due to skin friction provides generally provides sufficient pile capacity in almost all but the most unfavorable subsurface conditions. Given the prevalence of soft toe conditions, it is recommended that more research be undertaken to identify the underlying lapses in the construction methodology leading to these types of construction defects, as well as appropriate quality control measures aimed the minimizing their occurrence, as well as quality assurance measures aimed at identifying such constructions defects when they do occur.

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