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PREDICTION AND RELIABILITY OF PIPE PILES RESPONSE TO LATERAL LOADING

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ABSTRACT

Load-deflection relations of piles subjected to lateral loading are routinely required for design. The use of large diameter open pipe piles became common since its application as foundations for offshore structures, and more recently for bridge retrofitting and new construction designed for withstanding earthquake loading.

The accuracy and reliability of the analysis methods remains usually unknown as it requires the systematic examination of the measured performance of many piles. As part of a research aimed at developing the serviceability limit states for the AASHTO specifications, an evaluation of the methods predicting the response of piles to lateral loads was required.

This paper presents a database of laterally loaded open and closed pipe piles which were examined by various analysis methods. The performance of the methods when applied to open pipe piles and all pipe piles is reported along with practical conclusions for their use.

BACKGROUND

An ongoing project supported by the National Cooperative Highway Research Program (NCHRP Project 12-66) is aimed at developing and calibrating procedures and writing specifications for serviceability design of bridge foundations. The AASHTO specifications are based on Load and Resistance Factor Design (LRFD) principles with resistance factors obtained from probabilistic analysis of data, whenever possible.

Structures in general and bridges in particular are often limited in the ability to accommodate lateral displacements of the foundations. As such, serviceability of bridges is defined, among other ways, by the maximum (limiting) possible lateral displacements. AASHTO, 2006, and previous specifications are based on Moulton (1986) limiting total lateral displacement of bridge substructures to 1.5 inch and if combined with vertical displacement, to 1.0 inch only. For additional details regarding the serviceability limit state of bridges, see Paikowsky and Lu (2006). The development of resistance factors associated with the analysis of lateral response of a pile, one needs to assess the uncertainty in the prediction of the lateral resistance of driven deep foundations. This uncertainty was evaluated via the ratio between the measured lateral load to the one calculated for a given displacement, using case histories of laterally loaded piles.
METHODS OF ANALYSIS FOR LATERAL DISPLACEMENT OF A DEEP FOUNDATION

Overview

Methods of analysis of pile behavior under lateral loading widely range in complexity from simple and empirical methods to three-dimensional, non-linear finite element methods, modeling the pile-soil interaction with a great detail. As part of NCHRP project 12-66, a questionnaire was developed to evaluate the state of practice in highway bridge design and construction. The obtained results suggested that p-y curves were most commonly used by Geotechnical engineers in analyzing the behavior of laterally loaded piles in bridge design. Three known methods and empirically developed normalized relations were used for the comparison and are briefly reviewed in the following sections.

Equilibrium Method – Broms (1964a, 1964b)

Broms (1964a, 1964b) separated the analysis into cases of laterally loaded piles that are embedded in cohesive soils and in cohesionless soils. Broms also suggested different procedures for the prediction of laterally loaded piles under working loads and for the assessment of the pile’s ultimate resistance.

At the working state, Broms (1964a, 1964b) assumed that under loads less than one half to one third of the ultimate lateral resistance, the deflections of a single pile increases approximately linearly with the applied load. Subsequently, the unit soil reaction, p, acting on a laterally loaded pile increases in proportion to the lateral deflection y. For details on the application of Broms’ method, see Hannigan et al. (1996).

p-y Curves Method

In many cases the lateral loads are moderate to relatively high, for which nonlinearity typifies the pile load-deflection behavior. As a result, nonlinear elasticity methods have been developed in which the application of elastic solutions for equivalent soil properties is used in an iterative procedure, ending when displacement compatibility between soil and pile is achieved. The most commonly used such method is referred to as the “p-y curves method”, first devised by McClelland and Focht (1958) and improved over the years by others. In the p-y curves procedure, nonlinear curves relating the soil reaction (p) to the pile displacement (y) at various depths are first constructed. An initial stiffness of the soil is assumed, and the governing elastic differential equation of the pile’s deflection is solved numerically for that stiffness, resulting in a distribution of pile deflection. With the calculated deflection, entering the p-y curves, the soil reaction can be evaluated and compared with the one initially assumed. If a substantial difference exists, the soil stiffness at the depth for which the curve was drawn is taken as the secant modulus from the p-y curve at the previously computed deflection and the procedure is then repeated until tolerable compatibility is reached. Although not completely true, the Beam on Elastic Foundation (BEF) assumption at the base of the solution (Winkler’s assumption that
the soil reaction at any discrete depth is independent of all other depths) has been shown to produce accurate results for the patterns of deflections that can occur in practice (Matlock, 1970). Subsequently, three matters need to be considered: (1) the elastic analysis of the interaction between the soil and the pile, modeled using the concept of subgrade reaction, (2) the estimation of the shape of the p-y curves for various types of soil and loading conditions, and (3) the procedure in which nonlinearity is incorporated into the solution. A comprehensive review of the historic development of research on those three issues is provided by Duncan, et al. (1994).

According to the subgrade reaction approach, the laterally loaded pile is treated as a BEF. Winkler’s (1867) soil model is assumed in which the elastic soil medium is replaced by a series of infinitely closely spaced independent and elastic springs with stiffness equal to the modulus of horizontal subgrade reaction, \( k_h \):

\[
k_h = \frac{P}{y}
\]  

(1)

In cohesionless soils (and NC clays) the modulus of horizontal subgrade reaction increases linearly with depth. For overconsolidated clays \( k_h \) is usually assumed to remain constant with depth. This fact becomes important when attempting to solve the differential equation that describes the behavior of an elastic beam:

\[
EI \times \frac{d^4y}{dz^4} + p = 0
\]

(2)

where \( EI \) is the pile stiffness, and \( p \) is the soil reaction that is equal to \( k_hy \). Thus, the governing differential equation can be rewritten as follows:

\[
\frac{d^4y}{dz^4} + \frac{k_h(z) \times y}{EI} = 0
\]

(3)

Application of p-y curves analysis requires the use of computer codes to assess the deflections of the pile and the bending moments it develops under various loads. Relevant programs have been developed by Reese (1977, 1984, and 1985) and others. The programs used for the purpose of the presented work are COM624P (Wang and Reese, 1993) and LPile Plus 5.0 (Reese et al., 2004). Both programs are based on the same formulation and differ only in ease of use and some features. A thorough investigation of both programs resulted with identical solutions for all practical reasons, validating the interchangeable use of the programs (Paikowsky, 2005).

**Strain Wedge Method**

In the strain wedge (SW) model approach (Norris 1986), the traditional one-dimensional BEF pile response parameters are characterized in terms of three-dimensional soil-pile interaction. The SW model parameters are related to an envisioned three-dimensional passive wedge of soil developing in front of the pile. The SW model provides a theoretical link between the more complex three-dimensional soil-pile interaction and the simpler one-dimensional BEF
characterization, and allows the appropriate selection of BEF parameters to solve the fourth-order ordinary BEF differential equation 2.

One of the main assumptions of the SW model is that the deflection pattern of the pile is taken to be linear over the controlling depth of the soil near the pile top, resulting in a constant deflection angle, Norris (1986), Ashour and Norris (2000). The computer code SWM 6.0 was used for analyzing the presented case histories.

Normalized Relations

Based on the case histories assembled for the project’s database, an attempt was made to develop a normalized lateral load-displacement relation for providing a simplified first approximation. Figure 1 presents the best-fit line relation (and the range of the data) between the applied lateral load and the displacement normalized by the pile’s diameter. The presented relations relate to large diameter ($\phi \geq 24''$) pipe piles with upper layer being sand (12 cases) and clay (20 cases), and the response of 13 cases of small diameter pipes ($12\frac{3}{4}'' \leq \phi \leq 18''$) in all soils. The normalized best-fit lines are then used as a prediction method for the pile response depending on the pipe pile diameter and upper soil layer condition.

DATABASE

Table 1 presents a summary of all single driven piles analyzed for lateral resistance categorized by pile size and method of analysis. The data is further separated between all pipe piles and open-ended pipe piles. For each subcategory the number of pile cases for which static lateral load test results were available and the number of various sites are provided; e.g. for p-y curves (COM624P/LPile) 33 load tests on pipe piles with outside diameter ($\phi$) greater than 24 inches at 5 different sites were analyzed. All load evaluations followed consistent and uniform procedures for establishing the parameters required in the analysis methods.

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Analysis Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COM624/LPile</td>
</tr>
<tr>
<td>All Pipe 12\frac{3}{4}''≤\phi≤18''</td>
<td>n=15, Ns=10</td>
</tr>
<tr>
<td>All Pipe \phi≥24''</td>
<td>n=33, Ns=5</td>
</tr>
<tr>
<td>Open-Ended 12\frac{3}{4}''≤\phi≤18''</td>
<td>n=7, Ns=3</td>
</tr>
<tr>
<td>Open-Ended \phi≥24''</td>
<td>n=14, Ns=5</td>
</tr>
</tbody>
</table>

n = number of cases analyzed  Ns = number of sites  $\phi$ = outside diameter of piles  COM624P/LPile - p-y finite difference computer program by FHWA / Ensoft  Broms - elastic solution, see Broms (1964a, b)  SWM - Strain Wedge Method based computer program, see User Manual SWM6.0  Normalized - normalized relations developed in this research using in-situ load-displacement data, Fig. 1
Figure 1. Applied lateral load vs. normalized deflection (with pile diam.) for large diameter pipe piles separated according to upper soil layer type, and small diameter pipe piles for all soil types based on best-fit line and range of cases for each group.

ANALYSIS RESULTS

Figures 2 to 5 and Table 2 summarize the database analyses. The data presents the statistical parameters when comparing measured to calculated lateral load for a given pile top displacement using different analysis methods. Table 2 provides the statistics of all cases combined. The data were divided for small and large diameter open-pipe piles (Figures 2 and 3, respectively), and all small and large diameter pipe piles (Figures 4 and 5, respectively). Figure 6 presents a flow chart for which all the results (48 cases) were summarized based on categorization according to soil type, pile size and mode of penetration for the p-y method of analysis under a (lateral) pile top displacement of 1.0 inch.

DISCUSSION OF RESULTS

Very reasonable agreement exists overall between the calculated to measured loads using the BEF approach either via p-y curves as defined by COM624P/LPile (Wang and Reese, 1993; Reese et al., 2004) or its evaluation via the Strain Wedge Method (SWM 6.0). In all categories containing significant amount of data, the bias of the method, $\lambda$ (measured over predicted), is about 1.1 and decreasing as the lateral displacement increases while the COV remains constant at about 0.35. Although
Table 2. Summary and Statistics for All Lateral Displacements of the Cases Shown in Figures 2 to 5.

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>OEP $\phi \leq$18”</th>
<th>OEP $\phi \geq$24”</th>
<th>All PP $\phi \leq$18”</th>
<th>All PP $\phi \geq$24”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$\lambda$</td>
<td>COV</td>
<td>$n$</td>
</tr>
<tr>
<td>p-y curve</td>
<td>34</td>
<td>0.842</td>
<td>0.406</td>
<td>44</td>
</tr>
<tr>
<td>Broms</td>
<td>34</td>
<td>0.803</td>
<td>0.492</td>
<td>47</td>
</tr>
<tr>
<td>SWM$^1$</td>
<td>34</td>
<td>0.896</td>
<td>0.304</td>
<td>43</td>
</tr>
<tr>
<td>SWM$^2$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>43</td>
</tr>
<tr>
<td>Normalized$^3$</td>
<td>24</td>
<td>1.233</td>
<td>0.360</td>
<td>-</td>
</tr>
<tr>
<td>Normalized$^4$</td>
<td>34</td>
<td>0.465</td>
<td>0.719</td>
<td>47</td>
</tr>
</tbody>
</table>

n – number of analyzed cases
COV – coefficient of variation

$\lambda$ - Bias of measured over calculated lateral load for the given displacement.

$^1$Soil profile and parameters used consistently in the research
$^2$Soil profile and parameters used in the reports presenting the case histories
$^3$Normalized relations based on small diameter piles
$^4$Normalized relations based on large diameter piles

Variation in the bias can be attributed to factors like penetration mode (open vs. close ended pipes), size and soil type (see Figure 6), it seems that the coupling of the subsurface variability (in and between the sites) with the method variability (by the nature of the database) does not allow to deduce conclusively regarding the significance of the other effects. It seems that the number of different sites used for each group case is a systematic factor affecting the results, i.e. a larger ratio of number of cases to number of sites results in a smaller COV for each investigated category. The open larger diameter (φ≥24”) pipe piles’ behavior was found to be very similar to that of the closed pile behavior, most likely because in most cases both pile types were filled with concrete (see Figure 6). The lower bias for the cases in which soil stayed in the open pipe during the testing suggests over-prediction (of load) compared to the measured values. This conclusion is limited, however, by the small number of cases analyzed. The smaller diameter open pipe piles behaved differently than the closed ended smaller diameter group. The close results obtained by the SWM when using the parameter selection procedure established in the research and that provided independently by the reports, suggest small sensitivity to independent ‘reasonable’ parameter selection.

Broms’ analysis provides a reasonable initial estimation of the lateral force for a given displacement. The method remains viable also for the large diameter piles both open and close ended. The method’s major deficiency is in having a linear relation of the force to the displacement over a wide range of displacements. As such, the curves presenting the bias of the method with the displacements (refer to Figures 2 to 5) slope sharply with the increase of the displacement.

The normalized relations developed as a first approximation are inherently limited to the pile sizes for which the normalization was developed for, the same as the coefficient of horizontal subgrade reaction (size dependent). This becomes evident when trying to predict the response of small diameter piles by the normalized
Figure 2. Graphical presentation of the bias of the lateral load (measured over calculated) and coefficient of variation vs. the lateral displacement of the pile top for open pipe piles (O.D. ≤ 18") (3 sites).

Figure 3. Graphical presentation of the bias of the lateral load (measured over calculated) and coefficient of variation vs. the lateral displacement of the pile top for open pipe piles (O.D. ≥ 24") (5 sites except for SWM analysis which had 4 sites).
Figure 4. Graphical presentation of the bias of the lateral load (measured over calculated) and coefficient of variation vs. the lateral displacement of the pile top for all pipe piles (O.D. ≤ 18”) (10 sites)

Figure 5. Graphical presentation of the bias of the lateral load (measured over calculated) and coefficient of variation vs. the lateral displacement of the pile top for all pipe piles (O.D. ≥ 24”) (5 sites, except SWM which had 4 sites)
Figure 6. Flow chart for the ratio between measured and calculated loads using p-y method (COM624P or LPile programs) at a lateral displacement $\delta h=1.0''$ for all pipe piles categorized based on soil type, size and mode of penetration.
relations for the large diameter piles (Figures 2 and 4). The parameters obtained in the analyses and presented for the normalized relations suggest the following:

1. The bias of the prediction for the small diameter pipe piles decreases sharply with the increase of the lateral pile head movement while that for the large diameter piles presents a moderate decrease with the increase of the lateral pile head displacement.

2. The COV varies according to pile type and size with the largest variation noted for the smaller diameter pipe piles (for which there is a large number of sites relative to the number of cases). However, the COV remains about constant with the variation in the pile top displacement.

An independent evaluation of the normalized relations was carried out via an additional case history of a large diameter pipe pile ($\phi=24"$, in clay). The pile was analyzed using the same normalized relations first established without this case. The examined case history (30-1-PP) had a bias varying between 0.528 to 0.561, which differs significantly from the other cases used to establish the best-fit normalized relations for the large diameter pipes. The database cases generally resulted with biases varying from 0.743 to 1.890, mostly around 0.9±0.1 for all 32 cases. If the normalized relations were to be updated with this single case history, its influence on the new best-fit relations would be minimal. It can, therefore, be concluded that the validity of the established normalized relations needs to be examined via a larger number of independent case histories.

SUMMARY AND CONCLUSIONS

The behavior of pipe piles under lateral load is particularly important due to the following reasons:

1. It is a preferable pile type in offshore and water-crossing construction projects as well as bridge retrofitting for earthquake loads.

2. Large variability in the response due to the influence of the method of installation (e.g. open vs. closed ended) on the surrounding soil and stiffness depending upon final construction details (i.e. empty, soil or concrete filled pile) would result in variation of the pile’s response.

The major conclusions following the presented data are:

1. Reasonable first approximation was obtained by using Broms analysis and/or normalized relations with the later subjected to the limitations of the database used for its establishment. The Broms method assumes linear load-displacement relations and hence its accuracy is subjected to the magnitude of the displacement. The normalized relations are size dependent and hence separate relations need to be developed based on pile size.

2. The methods utilizing Beam on Elastic Foundation approach either via p-y curves directly or Strain Wedge assumption lead to a very good prediction of all lateral pipe piles behavior. Considering the accuracy of load-displacement analyses in any geotechnical related field (e.g. vertical displacements of foundations, etc.) the use of the p-y method is proven repeatable and accurate.

3. Figure 6 investigates the uncertainty of the prediction of lateral pipe pile loads for a lateral displacement of 1.0 inch considering soil type, penetration mode
and pile size. The information presented in the flow chart of Figure 6 is of particular interest as it refers to the maximum recommended (service) lateral displacements when combined with vertical displacement. The information presented suggests the following:

a. The uncertainty associated with the prediction of the forces for the larger pile sizes is significantly smaller than that for the smaller pile sizes (COV=0.21 vs. COV=0.63). This can be related to the ratio of number of case histories to number of tested sites (6.6 to 1 and 1.5 to 1 for large and small size piles, respectively).

b. Excluding the piles tested in fill (4 cases only), the bias of the predictions for piles in clay is similar to that in granular soils with larger uncertainty for piles in granular soils.

c. The prediction of the displacement of soil filled pipe piles exhibited systematic over-prediction (bias=0.70) compared to concrete filled open or closed driven pipe piles (bias=1.10 and 1.27, respectively). These values are limited however to small number of cases (n=5) in comparison to n=16 and n=27 in the concrete filled piles.

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(iv) SWM6.0 was provided by Drs. Gary Norris and Muhamad Ashour.

(v) Mr. Zeidan Ashraf investigated the lateral response of pipe piles (UML vol. #88) as part of his undergraduate project at the Technion – Israel Inst. of Tech. Ms. Mary Canniff of GTR had organized & sorted the databases, assembled & compiled the questionnaire, and contributed in putting together this manuscript.

DISCLAIMER

The research presented here is part of an ongoing NCHRP project, which is aimed at writing the AASHTO Serviceability Limit State Design of Bridge Foundation. The opinions and conclusions expressed or implied in the paper are those of the entities/individuals performing the research and are not necessarily those of the TRB, the National Research Council, AASHTO, or the individual states participating in the National Cooperative Highway Research Program.
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SWM6.0 User Manual Strain Wedge Model Computer Program.