Title: Incorporating Long-term Set-up into Load and Resistance Factor Design of Driven Piles in Sand

Article Author: Luo Yang; Robert Liang

Author’s Affiliation and Address:
Luo Yang, Project Engineer, Fugro-McClelland Marine Geosciences, Inc. 6100 Hillcroft, Houston, TX 77081; Phone: 713-369-5630; Fax: 713-369-5570; Email: lyang@fugro.com.
Formerly, graduate student in Univ. of Akron.
Robert Liang, Professor, Dept. of Civil Engineering, Univ. of Akron, Akron, OH 44325-3905; Phone: 330-972-7190; Fax: 330-972-6020; Email: rliang@uakron.edu

Author Responsible for Correspondence:
Luo Yang
Fugro-McClelland Marine Geosciences, Inc.
6100 Hillcroft, Houston, TX 77081
Phone: 713-369-5630
Fax: 713-369-5570
Email: lyang@fugro.com

This paper is submitted to the TRB 86th Annual Meeting Committee (AFS30) for the technical session “Soil Set-up and Relaxation Effects on Bearing Capacity of Driven Piles”. In this paper, the number of words in text is about 4500; the number of tables is 4; the number of figures is 6.
ABSTRACT: It has been known that after initial pile driving, pile capacity gain over time (set-up) could constitute a significant portion of the total pile capacity. In the past, there has been very little guidance for incorporating pile set-up capacity in design. This may be due to large uncertainties involved in predicting the pile set-up. A comprehensive statistical database is developed to describe the set-up for piles driven into sand. Based on the collected pile testing data, pile set-up is significant and continues to develop for a long time after pile installation. The mechanisms of pile set-up in sand are discussed in detail. The statistical database shows that lognormal distribution can be used to properly describe the probabilistic characteristics of the predicted set-up capacity using Skov and Denver’s equation. The main objective of this paper is to incorporate the set-up effect into a reliability-based Load and Resistance Factor Design (LRFD) of driven piles in sand. First Order Reliability Method (FORM) is used to derive separate resistance factors that would account for different degrees of uncertainties associated with measured short-term capacity and predicted set-up capacity. The incorporation of set-up effects in the LRFD helps improve the prediction of total capacity of driven piles, resulting in more economical design. A practical design procedure within LRFD framework to incorporate the pile set-up effects is outlined at the end of the paper.

INTRODUCTION

Pile set-up in sand was first reported by Tavenas and Audy (1) and Samson and Authier (2). Subsequently, a number of other case histories have been reported in the literature. Chow et al. (3) summarized the results from 11 case histories with long-term set-up effects for driven pile in sand, indicating that most of pile capacities increase by around 50% (±25%) per log cycle of time from 1 day after pile driving. It means that, compared to the pile capacities at 1 day after pile driving, the pile capacities approximately increase half at 10 day after pile driving and one time at 100 day after pile driving. Long et al. (4) also compiled a database of set-up cases, and categorized the soil into three main groups: clayey soil, mixed soil, and sand. The sand group contained 6 case histories; many of them are the same as in Chow et al. (3). Axial pile capacity was found to increase from 30% to more than 100% of the pile capacity at the end of driving (EOD). Axelsson (5) presented a database showing the set-up rate ranging from 15% to 65% per log cycle of time. Komurka et al. (6) provided an extensive bibliography related to the topic of pile set-up. Although there are a number of observed data on pile set-up, the beneficial effect of long-term set-up of driven piles in sand has very seldom been utilized to any significant extent in piling projects, due to high uncertainties of predicting the development of set-up.

Recently, with an accumulation of more data and knowledge on set-up phenomenon, some researchers have suggested that the set-up be formally incorporated into the prediction method to determine total pile capacity. For example, Bullock et al. (7, 8) proposed a conservative method for incorporating side shear set-up into the total pile capacity. The predicted set-up capacity was assumed to have the same degree of uncertainties as the measured reference capacity; thus a single safety factor in ASD (Allowable Stress Design) was used to account for all uncertainties of loads and resistances. Recognizing different uncertainties associated with the measured initial capacity and the predicted set-up capacity, Komurka et al. (9) proposed a method to apply separate safety factors to EOD and set-up components of driven pile capacity. Furthermore, the set-up capacity was characterized as a function of pile penetration based on dynamic monitoring during both initial driving and restrike testing.

With the American Association of State Highway and Transportation Officials (AASHTO) migration from ASD method to LRFD method for foundation design, there is a need to develop separate resistance factors for measured short-term capacity and set-up capacity,
respectively. This paper presents a database containing a large number of pile testing data in sand, from which the set-up effect is statistically analyzed. The dynamic test results obtained during a short-time restrike (usually 1 day after initial pile driving) are used to predict the long-term capacity based on the formula proposed by Skov and Denver (10). The compilation of the statistical database of set-up capacity makes it possible to apply the reliability-based analysis techniques to develop separate resistance factors to account for different degrees of uncertainties associated with the measured reference capacity and the predicted set-up capacity. The First-Order Reliability Method (FORM) is used to calibrate the separate resistance factors for various target reliability levels. The application of separate resistance factors in LRFD for the measured reference capacity and the predicted set-up capacity can improve the prediction of driven pile capacity as well as reduce pile length or number of piles.

### A COMPILED DATABASE OF CASE HISTORIES

A database containing both static and dynamic load tests was collected and listed in Table 1 based on the published studies of the driven piles in sand. The database consists of 190 loading tests in total, performed on 73 piles where at least two separate tests at different times are performed on each pile to determine the set-up.

#### TABLE 1 Summary of load test database for driven piles in sand

<table>
<thead>
<tr>
<th>References</th>
<th>Site locations</th>
<th>Number of piles</th>
<th>Main soil type</th>
<th>Pile type</th>
<th>Depth (m)</th>
<th>Testing type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevenas and Audy, 1972 (1)</td>
<td>Canada</td>
<td>27</td>
<td>Uniform medium sand, SPT N=23</td>
<td>D=305mm Concrete hex.</td>
<td>8.5~13</td>
<td>Static</td>
</tr>
<tr>
<td>Samson and Authier, 1986 (2)</td>
<td>Canada</td>
<td>1</td>
<td>Medium sand, gravel</td>
<td>HP 12*63</td>
<td>22</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Seidel et al., 1988 (35)</td>
<td>Australia</td>
<td>1</td>
<td>Loose to dense sand</td>
<td>450*450mm prestressed concrete</td>
<td>10.5</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Skov and Denver, 1988 (10)</td>
<td>Germany</td>
<td>2</td>
<td>Medium to coarse sand</td>
<td>350*350mm concrete, and D=762mm pipe</td>
<td>21, 33.7</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Preim et al., 1989 (11)</td>
<td>USA</td>
<td>2</td>
<td>Loose to medium fine sand</td>
<td>355*355mm concrete, and D=323mm closed-end pipe</td>
<td>27, 25</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Svinkin et al., 1994 (18)</td>
<td>USA</td>
<td>6</td>
<td>Silty sand</td>
<td>457~915mm square concrete</td>
<td>19.5~22.9</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>York et al., 1994 (16)</td>
<td>USA</td>
<td>15</td>
<td>Medium dense sand</td>
<td>D=355mm monotube</td>
<td>10.7~21.6</td>
<td>Stat. &amp; WEAP</td>
</tr>
<tr>
<td>Chow et al., 1998 (3)</td>
<td>France</td>
<td>2</td>
<td>medium to very dense sand, Dr ~ 75%</td>
<td>D=324mm open-end pipe</td>
<td>11, 22</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Axelsson, 1998 (12)</td>
<td>Sweden</td>
<td>3</td>
<td>Loose to medium dense glacial sand</td>
<td>235*235mm concrete</td>
<td>19</td>
<td>CAPWAP</td>
</tr>
<tr>
<td>Attwooll et al., 1999 (37)</td>
<td>USA</td>
<td>1</td>
<td>Unsaturated, dense sand</td>
<td>D=324mm pipe</td>
<td>10.1</td>
<td>Stat. &amp; CAPWAP</td>
</tr>
<tr>
<td>Tan et al., 2004 (13)</td>
<td>USA</td>
<td>5</td>
<td>Loose to medium dense sand</td>
<td>356mm H-pile, D=610mm closed-end pipe</td>
<td>34~37</td>
<td>CAPWAP</td>
</tr>
<tr>
<td>Bullock et al., 2005 (7,8)</td>
<td>USA</td>
<td>3</td>
<td>Dense fine sand</td>
<td>457*457mm prestressed concrete</td>
<td>9~25</td>
<td>O-Cell</td>
</tr>
</tbody>
</table>
Table 1 provides information about the test pile, soil conditions of the site, and the sources of references. However, it should be noted that the database suffers from the following shortcomings:

- There exists a difference in the definition of the reference capacity $Q_{re}$. Tavenas and Audy (1) and Bullock et al. (7, 8) assessed $Q_{re}$ from tests conducted about 0.5 days after driving. In the remaining cases, $Q_{re}$ was defined as the measured capacity at EOD.
- The capacity was determined either by static or dynamic testing, but both dynamic and static load test results could have been used in the same test series without distinguishing them. Furthermore, the different static loading failure criteria have been used in the references.
- It is generally believed that the set-up mainly takes place along the pile shaft. However, only total capacity was available in this database, making it not possible to separate the toe and shaft capacities with sufficient accuracy in many cases in the database. The testing results from Bullock et al. (7, 8) are for changes in shaft capacity only.

![Figure 1 Case histories of pile set-up in the compiled database](image)

Pile axial capacities are shown to increase with time after driving in Fig. 1. It is noted that, in some cases, the long-term axial capacity after the installation reaches 3 to 4 times the axial capacity at EOD. Most of piles experience an increase of $20\%$ $\sim 100\%$ of EOD pile capacity. The soil types in the database vary from loose to dense sand. It can be seen that the piles driven into loose sand experience relatively more pronounced set-up, such as the cases reported by Preim et al. (11), Axelsson (12), and Tan et al. (13). The sizes of driven piles in the database are relatively uniform with the diameter in the range of 300$\sim$600 mm, such that it is not possible to investigate the effect of the pile size on the set-up. Therefore, it should be noted that
the statistical analysis results based on the compiled database must be carefully applied for the piles with the diameter out of this range.

No cases of relaxation in sand were found in the compiled database. Parsons (14) reported the relaxation of driven piles in New York area based on the reduction of pile penetration resistance in granular soils from EOD to BOR (beginning of restrike), but provided no alternative explanations for the observations. Yang (15) also reported the relaxation of piles in sand, but did not provide the actual load test results. York et al. (16) argued that the relaxation could be initiated in pile group when driving pile into saturated sand. Pile-driving vibrations densify the surrounding soils. Subsequently, driving additional piles may cause the sand to dilate rather than compress, resulting in the conditions for potential relaxation. However, York et al. (16) also proposed that set-up can occur following cessation of relaxation and result in a net increase of pile capacity.

**MECHANISM OF SET-UP IN SAND**

Set-up is defined as an increase in bearing capacity with time that takes place after pile installation. It is believed that excess pore pressures induced during driving dissipates very quickly in sand, usually within a few hours. Tavenas and Audy (1) first reported the well-documented cases of pile long-term set-up in sand, which was not attributable to pore pressure changes.

Based on the pile tests at Lebenne, Lehane et al. (17) presented that the ultimate shear stress, $\tau_f$, acting on a pile shaft could be described by the simple Coulomb failure criterion:

$$\tau_f = \sigma_{rf}' \tan \delta_f = (\sigma_{rc}' + \Delta \sigma_r') \tan \delta_f$$

(1)

Where $\sigma_{rf}'$ = total radial effective stress on pile shaft at the failure; $\delta_f$ = interface angle of friction at failure; $\sigma_{rc}'$ = radial effective stress on pile shaft at stationary equilibrium; and $\Delta \sigma_r'$ = increasing radial effective stress on pile shaft during pile loading (primarily due to the dilation).

Based on Equation (1), Chow et al. (3) attributed the long-term increase in pile capacity to three possible reasons: corrosions, effects of age on sand properties, and stress relaxation in the soil arching generated during pile driving. Chow et al. (3) demonstrated that the corrosion is unlikely to be the principle cause of pile set-up in sand, based on the observation that $\tau_f$ increased most apparently below the water table where corrosion tends to happen much slightly at Dunkirk. The compiled database in this paper show similar degrees of pile set-up development for the concrete (non-corroding material) and steel (corroding material) piles, further diminishing the notion that corrosion may contribute to pile set-up. Chow et al. (3) also argued that the marked set-up effects on driven piles were mainly due to the stress relaxation in the soil arching surrounding the pile shaft, resulting in an increase of $\sigma_{rc}'$. Changes in soil properties (such as shear stiffness and dilation angle) through soil aging were only believed to have little influence on the overall set-up.

In order to investigate the principle mechanisms behind long-term set-up of driven piles in sand, Axelsson (5, 12) investigated extensive full-scale field tests involving both dynamic testing and torque testing on driven rods, as well as dynamic and static testing on driven concrete piles instrumented with earth pressure cells on the shaft. The field test results from shaft earth pressure cell revealed that the horizontal stress on the pile shaft experienced a surprisingly large increase during the actual loading. It was concluded that the effect of increasing dilatant behavior due to soil aging in combination with soil particles interlocking with the surface roughness was the major cause of the observed long-term set-up of the piles. The earth pressure cell readings
with time also showed that the stress relaxation of soil arching surrounding the piles lead to an increase in horizontal stress on the pile shaft, which contributed in a minor degree to the long-term set-up of the piles. Bullock et al. (8) presented that the pile shaft showed set-up with similar average magnitudes in all soils, continuing long after the dissipation of pore pressures, and with long-term set-up due to aging effects at approximately constant horizontal effective stress. They suggested that much of the long-term set-up in sand occurs as a result of something other than increases in horizontal effective stress. The test results by Bullock et al. (7, 8) also demonstrated that the set-up mainly takes place along the pile shaft.

Based on review presented, one may surmise that the long-term set-up of the piles in sand could be attributed to two main causes: stress relaxation and soil aging. However, there was no strong consensus as to which one is the principle cause. Actually, the stress relaxation and the soil aging are interrelated in leading to the increase in the horizontal effective stress, dilatant behavior during loading, and soil particles interlocking with the shaft surface roughness. The magnitude of the long-term set-up of the piles in sand is primarily dependent on the pile dimension and other pile characteristics that would affect the disturbance of the surrounding sand and the increase of horizontal stress during loading, as well as the sand properties (i.e., stiffness, particle size, and particle shape). Further research is clearly necessary to investigate the effect of the above factors on the long-term set-up behavior.

EMPIRICAL RELATIONSHIPS

Empirical relationships have been proposed for predicting the set-up by many researchers. Skov and Denver (10) presented an empirical equation for the set-up based on a logarithmic increase of pile capacity with time. Svinkin et al. (18) developed a formula predicting the set-up based on load test data on five concrete piles in dense silty sand. Long et al. (4) proposed an equation predicting the rate at which the pile capacity increases with time. The equation proposed by Long et al. is very similar to Svinkin et al.’s where the pile capacity after installation is proportional to the time with an exponential efficiency. An alternative method of using a hyperbolic function to predict the set-up was proposed by Bogard and Matlock (19) and Tan et al. (13). Zhu (20) presented an equation for the set-up in soft clay based on the soil sensitivity. Huang (21) also presented a formula predicting the development of pile capacity in the soft soil of Shanghai, China. These empirical formulas are listed in Table 2.

Among those proposed formulas, the Skov and Denver (10) logarithmic empirical relationship in Eq. (6) has been commonly used for the prediction of the set-up by most of researchers. Based on Eq. (6), the predicted set-up capacity can be expressed as:

$$Q_{set-up} = Q_0 A \log \frac{t}{t_0}$$

(2)

where $Q_{set-up}$ = predicted set-up capacity at time $t$ after driving, $Q_0$ = measured axial capacity at time $t_0$, $A$ = a factor that is a function of soil type and can be determined as the slope of the linear portion of the normalized capacity $Q_{set-up}/Q_0$ versus log($t$) plot, $t$ = time since pile installation, and $t_0$ = time after installation at which the capacity gain becomes linear on a log($t$) plot.

Skov and Denver also recommended numerical values for $A$ and $t_0$ as 0.6 and 1 day in clay and 0.2 and 0.5 day in sand, respectively. Researchers such as Svinkin et al. (18), Camp and Parmar (22), and Bullock et al. (8), also provided a range of numerical values for these two parameters.
### TABLE 2 Empirical formulas for predicting pile capacity with time

<table>
<thead>
<tr>
<th>References</th>
<th>Equation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skov and Denver 1988 (10)</td>
<td>( Q_t = Q_0 (1 + A \log \frac{t}{t_0}) )</td>
<td>where ( t_0 = 0.5 ) and ( A = 0.2 ) in sand ( t_0 = 1.0 ) and ( A = 0.6 ) in clay</td>
</tr>
<tr>
<td>Svinkin et al. 1994 (18)</td>
<td>( Q_t = B Q_{EOD} t^{0.1} )</td>
<td>( B = 1.4 ) upper bound ( B = 1.025 ) lower bound</td>
</tr>
<tr>
<td>Long et al. 1999 (4)</td>
<td>( Q_t = 1.1 Q_{EOD} t^\alpha )</td>
<td>( \alpha ) values: average = 0.13, lower bound = 0.05, upper bound = 0.18</td>
</tr>
<tr>
<td>Bogard and Matlock 1990 (19)</td>
<td>( Q_t = \left[ 0.2 + 0.8 \left( \frac{t}{T_{50}} \right) \right] Q_u )</td>
<td>( Q_0 = ) ultimate capacity with 100% of setup realized ( T_{50} = ) time required to realize 50% of pile set-up</td>
</tr>
<tr>
<td>Zhu 1988 (20)</td>
<td>( Q_{14} = (0.375 S_I^t + 1) Q_{EOD} )</td>
<td>( Q_{14} = ) pile capacity at 14 day after EOD ( S_I = ) sensitivity of soil</td>
</tr>
<tr>
<td>Huang 1988 (21)</td>
<td>( Q_t = Q_{EOD} + 0.236 [1 + (Q_{max} - Q_{EOD}) \log t])</td>
<td>( Q_{max} = ) maximum pile capacity with 100% of setup realized</td>
</tr>
</tbody>
</table>

**Figure 2** Variation of normalized capacity with time based on Skov and Denver’s equation

Based on Skov and Denver’s equation, the normalized axial pile capacity (i.e., \( Q_t/Q_0 \)) versus the logarithm of time is plotted in Fig. 2 for the 47 pile cases where at least two separate load tests were performed after EOD. The reference capacity \( Q_0 \) was measured between 0.5 days to 2 days after EOD. The capacity \( Q_t \) was measured days, weeks, and months after EOD. The
dashed lines define an approximate range of $A$ from 0.1 to 0.9. The mean value of $A$ for all 47 testing piles is close to the value of 0.4.

**STATISTICAL STUDY OF PILE SET-UP**

Comparing Fig. 1 to Fig. 2, it can be found that the case taking $Q_{EOD}$ as the reference capacity shows more scattered normalized capacities than that taking $Q_0$ at 1 day after EOD. It can be attributed to the highly disturbed state of the soil during a brief period following installation that the initial rate of capacity gain with time is different from the later rate. During this period, the affected soil experiences an increase in effective and horizontal stress, consolidates, and gains strength in a manner, which is not well understood and is difficult to model and predict (Komurka et al. (6)). The use of $Q_{EOD}$ as the reference capacity inevitably needs to account for the high variability in the change of pile capacity in this period. Therefore, Skov and Denver’s equation where $t_0= 1$ day after driving is used to predict the set-up in the statistical study.

Based on the compiled database, most of pile testing data show that the pile capacity gain becomes approximately linear with the logarithm of time 1 day after pile installation. Researchers, such as Svinkin et al. (18), Axelsson (5, 12), McVay (23), and Bullock et al. (7, 8), have proposed the use of $t_0 = 1$ day in Skov and Denver’s equation. The time $t_0$ is a function of the soil type, the permeability and sensitivity of the soil, the pile type, and the permeability and size of the pile. The less permeable the soil and pile and the greater volume of soil displaced by pile driving, the longer the time $t_0$. The $A$ parameter is a function of soil type, pile material, type, size, and capacity, to account for the degree of the capacity gain with the elapse of time (Camp and Parmar (22); Svinkin et al. (18); Svinkin and Skov (24)). Although there should be physical meanings behind these parameters, both the parameters $t_0$ and $A$ are back-calculated from field data (e.g., Skov and Denver (10); Svinkin et al. (18); Chow et al. (3); Axelsson (5, 12); Camp and Parmar (22); Bullock et al. (7, 8)). It should be noted that the determination of $A$ is dependent on the value used for $t_0$, and visa-versa; these two variables are not independent.

Chow (3) reported the values of $A$ around 0.5 (±0.25). Studies by Axelsson (5) yielded the average value of 0.4 for $A$, with a range from 0.15 to 0.65. The observations from the compiled database in Fig. 2 seem to confirm the previous experiences. Therefore, the reference time $t_0 = 1$ day and $A = 0.4$ are used for the subsequent statistical analyses in this paper. When further data becomes available, the values of $t_0$ and $A$ could be modified. Most of pile tests are performed in 30 days after EOD in the compiled database. It can be seen that pile capacity increases approximately linearly with the logarithm of time within 30 days after EOD. Tevenas and Audy (1) concluded that the ultimate pile capacity increase during the first 15 to 20 days after EOD could be 70% higher than that observed at 0.5 day. Studies by York et al. (16) showed that set-up could have approached a maximum value within 15 to 25 days. Although some piles in the compiled database exhibit set-up after months or years; nevertheless, the increase of pile capacity with time after 30 days becomes less pronounced compared to those during the first 30 days after driving. Therefore, 30 days after EOD can be conservatively taken as the time after which the set-up effect in sand would be minimal.

The accuracy of Skov and Denver’s equation is analyzed by examining the ratio of the measured set-up capacities to the predicted using $t_0 = 1$ day and $A = 0.4$. The frequency distribution for 47 piles is shown in Fig. 3. It can be seen that a lognormal distribution seems to be able to represent the distribution. The mean value $\mu_{\ln x}$ and standard deviation $\sigma_{\ln x}$ of the fitted lognormal distribution are -0.122 and 0.538, respectively. To verify the assumed theoretical lognormal distributions, the Kolmogorov-Smirnov test (Ang and Tang (25)) was carried out. Fig. 4 shows the empirical cumulative frequency and the theoretical cumulative distribution of the
ratio of the measured to the predicted set-up capacity. Based on the Kolmogorov-Smirnov test, the critical value $D_n$ for the sample size of the compiled database is 0.200 at the 5% significance level. The maximum difference in cumulative frequency between the observed data and the theoretical distributions is $D_n = 0.096$, that is smaller than the critical value of 0.200 at the 5% significance level. Therefore, the assumed lognormal distribution for the ratio of the measured set-up capacities to the predicted set-up capacity is valid.

Figure 3 Frequency distribution of the ratio of measured set-up capacities to the predicted

Figure 4 Kolmogorov-Smirnov test for assumed lognormal distribution
CAPWAP approach (Rausche et al. (26, 27)) has been widely used for quality control and capacity determination of driven piles. Also, most of pile testing data in the compiled database are from CAPWAP results; therefore, CAPWAP approach is recommended for determining the measured short-term capacity $Q_0$. The bias factors of set-up capacity is calculated as the mean value of the ratio of the measured pile capacity to the predicted pile capacity by Skov and Denver’s equation where $A=0.4$ and $t_0=1$ day. The statistical analysis results of the predicted set-up capacity by the Skov and Denver’s equation, along with those for the CAPWAP BOR capacity are summarized in Table 3. Comparing the COV values, it is found that predicting pile set-up effect involves significantly higher uncertainties than measuring capacity $Q_0$ by CAPWAP BOR. Therefore, it is necessary to separate the resistance factors to account for the different degrees of uncertainties associated with the measured reference capacity and the predicted set-up capacity. The relationship between the measured reference capacity $Q_0$ and the predicted set-up capacity $Q_{set-up}$ is not at all clear. However, since the uncertainties of pile set-up prediction are mainly due to empirical relationship of Skov and Denver, it may be reasonable to assume that the measured $Q_0$ by CAPWAP and the predicted $Q_{set-up}$ by Skov and Denver are independent of each other. In this paper, the uncertainties associated with dead and live loads as well as the measured reference capacity $Q_0$ and the predicted set-up capacity $Q_{set-up}$ are systemically accounted for in a framework of FORM. Separate resistance factors are derived for $Q_0$ and $Q_{set-up}$ for adoption in the LRFD of driven piles in sand.

**TABLE 3 Probabilistic characteristics of random variables of loads and resistances**

<table>
<thead>
<tr>
<th>Random variables</th>
<th>Bias factor $\lambda$</th>
<th>Standard deviation $\sigma$</th>
<th>Coefficient of variation, COV</th>
<th>Distribution type</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_0$</td>
<td>1.158</td>
<td>0.393</td>
<td>0.339</td>
<td>Lognormal</td>
<td>Paikowsky et al.(29)</td>
</tr>
<tr>
<td>$Q_{set-up}$</td>
<td>1.023</td>
<td>0.593</td>
<td>0.580</td>
<td>Lognormal</td>
<td>Current Study</td>
</tr>
<tr>
<td>$L_L$</td>
<td>1.150</td>
<td>0.230</td>
<td>0.200</td>
<td>Lognormal</td>
<td>AASHTO (Nowak (28))</td>
</tr>
<tr>
<td>$L_D$</td>
<td>1.050</td>
<td>0.105</td>
<td>0.100</td>
<td>Lognormal</td>
<td>AASHTO (Nowak (28))</td>
</tr>
</tbody>
</table>

**PRACTICAL LOAD AND RESISTANCE FACTORS**

When incorporating the set-up effect into the design of driven pile, the LRFD criterion can be expressed as

$$\phi_0 Q_0 + \phi_{set-up}Q_{set-up} \geq \gamma_L L_L + \gamma_D L_D$$  (3)

where $\phi_0$ and $\phi_{set-up} =$ resistance factors for reference resistance at $t_0$ and set-up resistance, respectively; $Q_0$ and $Q_{set-up} =$ measured reference resistance at $t_0$ and predicted set-up resistance, respectively; $\gamma_L$ and $\gamma_D =$ load factors for live and dead loads, respectively; $L_L$ and $L_D =$ live load and dead load, respectively.

The probabilistic characteristics of the random variables $L_D$ and $L_L$ are well documented in AASHTO by Nowak (28). The probabilistic characteristics of the random variables $Q_0$ is taken from Paikowsky et al. (29). The probabilistic characteristics of the random variables $Q_{set-up}$, according to the compiled database, are described as a lognormal distribution. Table 3 summarizes the statistical parameters and distribution function for each random variable. With the known load and resistance statistical characteristics, the iterative solution of FORM approach can be applied to determine the load and resistance factors for the chosen target reliability index. Detailed descriptions and applications of FORM can be found in Ang and Tang (30), Phoon et al. (31, 32), Paikowsky et al. (29), and Allen et al. (33).

For a given reliability index $\beta$ and probability distributions for resistance and load effects, the partial safety factors determined by the FORM approach may differ for different failure
modes. For this reason, calibration of load and resistance factors is important in order to maintain the consistence with the current experience in LRFD. As suggested in NCHRP Report 507 (Paikowsky et al. 29), the target reliability index of $\beta=2.33$ corresponding to the probability of failure $P_f = 1\%$ is recommended for redundant piles defined as 5 or more piles per pile cap; the target reliability index of $\beta=3.00$ corresponding to the probability of failure $P_f = 0.1\%$ is recommended for nonredundant piles defined as 4 or fewer piles per pile cap. The resistance factors are $\Phi_0 = 0.65$ and $\Phi_0 = 0.50$ for CAPWAP approach at $\beta=2.33$ and $\beta=3.00$, respectively. As specified by AASHTO (Novak 28), the load factors $\gamma_L=1.75$ and $\gamma_D=1.25$ are used for live and dead loads, respectively. The above load and resistance factors can be used to determine the resistance factor $\Phi_{set-up}$ for predicted set-up capacity in the following algorithm based on the FORM approach.

$$\Phi_{set-up} = \frac{\gamma_L \mu_{L_L} + \gamma_D \mu_{L_D} - \Phi_0 \mu_{Q_0}} {\lambda_{Q_0}} \left( \frac{\mu_{Q_{set-up}}}{\lambda_{Q_{set-up}}} \right)$$  \hspace{1cm} (4)$$

where $\mu_{L_L}$, $\mu_{L_D}$, $\mu_{Q_0}$, and $\mu_{Q_{set-up}}$ are the mean values of random variables $L_L$, $L_D$, $Q_0$, and $Q_{set-up}$, respectively, calculated from FORM approach; $\lambda_{L_L}$, $\lambda_{L_D}$, $\lambda_{Q_0}$, and $\lambda_{Q_{set-up}}$ are the bias factors of random variables $L_L$, $L_D$, $Q_0$, and $Q_{set-up}$, respectively.

![Figure 5 Variation of resistance factor for $Q_{set-up}$ versus the ratio of dead load to live load](image)

Fig. 5 shows the effect of the variation of the ratio of dead to live load on the calculated resistance factors for predicted set-up capacity at the reliability level $\beta=2.33$ and $\beta=3.00$, respectively. The load factors for dead and live loads and the resistance factor for $Q_0$ are fixed as mentioned earlier when calculating the resistance factor for $Q_{set-up}$. It can be seen that the calculated resistance factor for $Q_{set-up}$ decreases slightly with an increase in the ratio of dead to live load. In general, however, the calculated resistance factor for $Q_{set-up}$ is not very sensitive to the ratio of dead to live load. Based on AASHTO (34), the ratio of dead to live load is a function
of a bridge’s span length and increases with the increase in the bridge’s span length. The ratio of dead to live load for the bridge with the span length of 60 m is recommended as 3.5. Therefore, the calculated resistance factor for $Q_{\text{set-up}}$ can be conservatively taken as 0.4 for the span length less than 60 m for the target reliability index $\beta=3.00$, when the predefined resistance factor for $Q_0$, dead load factor, and live load factor are 0.50, 1.25, and 1.75, respectively. The resistance factor for $Q_{\text{set-up}}$ can be conservatively taken as 0.5 for the span length less than 60 m for the target reliability index $\beta=2.33$, when the predefined resistance factor for $Q_0$, dead load factor, and live load factor are 0.65, 1.25, and 1.75, respectively.

<table>
<thead>
<tr>
<th>Random variables</th>
<th>Bias factor $\lambda$</th>
<th>Coefficient of variation COV</th>
<th>Partial safety factor ($\beta=2.33$)</th>
<th>Partial safety factor ($\beta=3.00$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_0$</td>
<td>1.158</td>
<td>0.339</td>
<td>0.65</td>
<td>0.50</td>
<td>Paikowsky et al.(29)</td>
</tr>
<tr>
<td>$Q_{\text{set-up}}$</td>
<td>1.023</td>
<td>0.580</td>
<td>0.50</td>
<td>0.40</td>
<td>Current Study</td>
</tr>
<tr>
<td>$L_L$</td>
<td>1.150</td>
<td>0.200</td>
<td>1.75</td>
<td>1.75</td>
<td>AASHTO (Nowak (28))</td>
</tr>
<tr>
<td>$L_D$</td>
<td>1.050</td>
<td>0.100</td>
<td>1.25</td>
<td>1.25</td>
<td>AASHTO (Nowak (28))</td>
</tr>
</tbody>
</table>

The recommended load and resistance factors are tabulated in Table 4 for different reliability levels. The corresponding $F.S.$ (Factor of Safety) in ASD (Allowable Stress Design) can be calculated as follows:

$$F.S. = \frac{\gamma_{D}L_D / L_L + \gamma_{L}}{\phi_{0}Q_0 / Q_{\text{set-up}} + \phi_{\text{set-up}}}$$

Fig. 6 shows the relationship between the corresponding $F.S.$ in ASD and the ratio of dead to live load. The corresponding $F.S.$ decreases with an increase in the ratio of dead to live load. The corresponding $F.S.$ are about 2.40 and 3.00 for the recommended load and resistance factors at target reliability index $\beta=2.33$ and $\beta=3.00$, respectively.
PROPOSED PROCEDURE TO INCORPORATE SET-UP INTO LRFD OF DRIVEN PILES IN SAND

The incorporation of set-up effect can efficiently improve the estimation of total capacity of driven piles so that pile length or numbers of piles can be economically reduced. The proposed procedure for incorporating set-up into LRFD of driven piles in sand is illustrated as follows:

1. Assign a pile diameter, length, and type for preliminary design using available site information and a static analytical design method.
2. Perform CAPWAP dynamic testing 1 day after pile installation and record the measured capacity as $Q_0$.
3. Estimate the set-up capacity based on the proposed semi-logarithmic empirical relationship:
   \[ Q_{\text{set-up}} = Q_0 A \log \frac{t}{t_0} \]
   (where $A = 0.4$, $t = 30$ days, and $t_0 = 1$ day).
4. Use the recommended resistance and load factors in Table 4 and the following formula,
   \[ \phi_0 Q_0 + \phi_{\text{set-up}} Q_{\text{set-up}} \geq \gamma_L L_L + \gamma_D L_D , \]
   to evaluate the reasonableness of the preliminary design.
5. Based on the result from step 4, change the pile diameter, length or number as desired to optimize the design.

The engineering judgment is very important in a given project site when using the proposed procedure to consider the set-up capacity, because the database in this paper is collected based on a wide range of site variability. The site-specific experience on set-up capacity is more desirable when the pile test results are available to estimate the development of long-term set-up at the given site.

Also, it is recommended that additional pile testing data be obtained to supplement the current database, thus allowing for more comprehensive statistical analysis of the pile set-up and more detailed investigation on the set-up mechanism. As it is generally believed that the set-up mainly takes place along the pile shaft, monitoring the separate set-up development along the shaft and at the toe is desirable to identify the set-up mechanism. CAPWAP analysis is recommended for the monitoring of the set-up development, since it is one of the most widely acceptable and efficient methods and has the ability to separate shaft and toe resistances. The time of the CAPWAP performed is suggested as EOD, 1 day, 10 days, 30 days, and 100 days after pile driving. Soil and pile properties are also desirable to be reported with the CPWAP testing results to supplement the current database. The soil properties, including friction angles, relative densities, and particle sizes and shapes, are believed to be the primary factors affecting the set-up development. The pile materials, types, and geometry are needed to clarify the relationship between the pile properties and the set-up effect.

CONCLUSIONS

A database of pile set-up capacity in sand has been compiled and presented in this paper. The compiled database showed that the logarithmic empirical relationship proposed by Skov and Denver (10) could be used to predict pile set-up. The reference time $t_0 = 1$ day and mean value $A = 0.4$ were suggested for Skov and Denver’s equation. The pile set-up database indicated that the time duration of 30 days after EOD may be considered as the point after which the set-up effect would be minimal. Based on the Kolmogorov-Smirnov test, the lognormal distribution was shown to adequately represent the probabilistic characteristics of the ratio of the measured set-up capacity to the predicted pile set-up capacity. The mean value $\mu_{\ln x}$ and the standard deviation $\sigma_{\ln x}$ of the fitted lognormal distribution are -0.122 and 0.538, respectively.
The statistical parameters of the pile set-up capacity derived from the compiled database, together with previous statistical analysis of CAPWAP BOR published by Paikowsky et al. (29), were systematically incorporated within the framework of FORM to calibrate the resistance factors for the predicted set-up capacity by Skov and Denver equation using the load conditions specified in AASHTO by Novak (28). The incorporation of set-up effect into the prediction of total pile capacity gives advantageous contribution to the estimated total pile capacity. For piles driven into sand, the resistance factor for $Q_{set-up}$ can be taken as 0.4 for a bridge span length less than 60 m if a target reliability index $\beta=3.00$ is chosen and the pre-set resistance factor for $Q_0$, dead load factor, and live load factor are 0.50, 1.25, and 1.75, respectively. The resistance factor for $Q_{set-up}$ can be taken as 0.5 for a bridge span length less than 60 m if a target reliability index $\beta=2.33$ is chosen and the pre-set resistance factor for $Q_0$, dead load factor, and live load factor are 0.65, 1.25, and 1.75, respectively. The corresponding F.S. in ASD are about 2.40 and 3.00 for the recommended load and resistance factors in LRFD at the target reliability index $\beta=2.33$ and $\beta=3.00$, respectively.

REFERENCES


