**Development of cyclic p-y curves for laterally loaded pile based on T-bar penetration tests in clay**

<table>
<thead>
<tr>
<th>Journal:</th>
<th><em>Canadian Geotechnical Journal</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cgj-2015-0358.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>16-Feb-2016</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Wang, Teng; China University of Petroleum, Department of Offshore Engineering</td>
</tr>
<tr>
<td></td>
<td>Liu, Wenlong; China University of Petroleum, Department of Offshore Engineering</td>
</tr>
<tr>
<td>Keyword:</td>
<td>cyclic p-y curve, strength degradation, laterally loaded pile, T-bar penetration tests</td>
</tr>
</tbody>
</table>

https://mc06.manuscriptcentral.com/cgj-pubs
Development of cyclic $p-y$ curves for laterally loaded pile based on T-bar penetration tests in clay

Teng Wang(corresponding author)
Department of Offshore Engineering
China University of Petroleum
No. 66, Changjiang West Road, Huangdao District, Qingdao, China
Tel: +86 15165283065
Email: wteng73@upc.edu.cn

Wenlong Liu
Department of Offshore Engineering
China University of Petroleum
No. 66, Changjiang West Road, Huangdao District, Qingdao, China
Email: 1033978480@qq.com

Submitted as Technical Paper

Words: 3911 (excluding references and acknowledgement)
Figures: 13
Tables: 3
Development of cyclic $p$-$y$ curves for laterally loaded pile based on
T-bar penetration tests in clay

Abstract

Offshore pile foundations are always subjected to cyclic lateral loads, which can result in the remolding and softening of the surrounding seabed soil. Cyclic T-bar penetrometer testing provides a rapid and effective method for assessing the remolded shear strength. It is widely believed that the soil strength degrades with the accumulation of plastic strain, but the strain cannot be measured. Numerical analysis of this paper shows that the accumulated plastic displacement of T-bar in a cyclic range of two diameters is approximately equal to its accumulated displacement. By using T-bar test data, a cyclic degradation model based on the accumulated (plastic) displacement is developed to describe the soil strength degradation at a desired depth. Furthermore, an improved $p$-$y$ curve model based on cyclic degradation model is proposed to estimate the lateral response of pile under cyclic loads. The improved $p$-$y$ curve model is embedded into the OpenSees program to investigate the cyclic lateral responses of single soil element and pile. A case study is conducted to verify the improved $p$-$y$ curve model by comparing with the published centrifuge experiment data. Results indicate that the improved $p$-$y$ curve model based on T-bar tests data is with high precision and practicability.

Keywords: cyclic $p$-$y$ curve; strength degradation; laterally loaded pile; T-bar penetration tests
Introduction

Coastal and offshore structures supported by pile foundations are always subjected to cyclic lateral loads due to the harsh environmental conditions, such as earthquake excitation, wind loads, sea waves or currents. It is observed that large lateral cyclic displacement may form a gap between pile and soil, and the softening of the soil often occurs under cyclic loading. For piles subjected to the cyclic lateral loads, one of the major concerns is the degradation of soil strength under cyclic loading. Matlock et al. (1978) first proposed the degradation equation to model the stiffness and/or strength degradation of soil-pile load-transfer curves, i.e. $p-y$ curve under cyclic loadings. The soil strength was assumed to degrade exponentially with the number of cycles in Matlock’s degradation equation, and similar degradation equations can be found from semi-empirically derived $p-y$ curve models (Grashuis et al. 1990; Rajashree and Sundaravadivelu 1996; Allotey and El Naggar 2008). In addition, Some semi-theoretically derived $p-y$ curve models (Trochanis et al. 1991; Badoni and Makris 1996; Gerolymos and Gazetas 2005a, 2005b) based on Bouc-Wen degrading hysteretic model (Bouc 1971; Wen 1976) were successively proposed to describe cyclic $p-y$ relationships of pile and soil with consideration to loss of strength. Heidari et al. (2013, 2014) extended Allotey et al.’s model (Allotey and El Naggar 2008) by generating $p-y$ curves based on the strain wedge method (SWM) (Ashour et al. 1998), which can take account of the basic pile and soil properties, such as pile cross-section shape, pile head condition, effective unit weight and undrained shear strength. Boulanger et al. (1999)
developed a dynamic \( p-y \) curve model that can take account of the nonlinear soil behavior, gap formation in cohesive soils, drag force, and soil damping, but this model cannot consider the degradation of the ultimate lateral capacity. However, the degradation of existing \( p-y \) curves is never explicitly linked to the soil properties. For example, it might be expected that the ultimate resistance of the cyclic curve would be the monotonic ultimate resistance divided by the sensitivity. Therefore, an improvement of this method is necessary and is made in this study.

Full-flow penetrometers (T-bar and ball) are increasingly used recently to obtain the accurate undrained shear strength and remolded strength characteristics through cyclic degradation testing in offshore site investigations (Yafrate et al. 2009). Based on the cyclic T-bar and ball penetration tests in clay, Einav and Randolph (2005) developed a soil strength degradation model using the accumulated absolute plastic shear strain. Since the accumulated displacement can be measured directly in cyclic T-bar penetration tests, a cyclic soil strength degradation model based on the accumulated displacement from in-situ T-bar testing is developed in this study. By incorporating it into the Boulanger model (Boulanger et al. 1999), an improved \( p-y \) curve model considering the softening of soil springs is proposed to predict the lateral response of pile under cyclic loading in soft clay. The improved model is embedded into OpenSees program (Mazzoni et al. 2007) to simulate cyclic \( p-y \) curves of soil elements and cyclic responses of pile. A case study is conducted to compare the load-displacement curves of pile simulated using the improved model with the results from the centrifuge.
experiments.

**Model description**

**Boulanger model**

Boulanger et al. (1999) developed a dynamic $p-y$ method to analyze seismic soil-pile-structure interaction. The nonlinear $p-y$ behavior is described by elastic spring ($p-y^e$), plastic spring ($p-y^p$), and gap spring ($p-y^g$). The gap component consists of a nonlinear closure spring ($p^c-y^g$) in parallel with a nonlinear drag spring ($p^d-y^g$).

The plastic spring acts rigidly when $-C_r p_{ult} < p < C_r p_{ult}$, where $C_r$ is the ratio of $p/p_{ult}$ when plastic yielding first occurs in virgin loading. Beyond the rigid range, the plastic spring is described by

$$p^p = p_{ult} - (p_{ult} - p_0) \left( \frac{c y_{50}}{c y_{50} + y_0^p - y_0^p} \right)^n$$

where $p_{ult}$ is the ultimate lateral capacity that keeps constant for a certain soil layer; $p_0 = p$ and $y_0^p = y^p$ at the start of the current plastic loading cycle; Coefficients $c$ and $n$ control tangent module of the plastic spring and curve sharpness respectively; and $y_{50} = 2.5 D \varepsilon_{50}$, where $\varepsilon_{50}$ is strain at which 50% of $p_{ult}$ is mobilized in a compression test.

The nonlinear drag spring which represents the residual resistance of the soil when the pile moves through the gap can be defined as follows:

$$p^d = C_d p_{ult} - (C_d p_{ult} - p_0^d) \frac{y_{50}}{y_{50} + 2 |y^d - y_0^d|}$$

where $C_d$ controls the maximum drag force, $p_0^d = p^d$ and $y_0^d = y^d$ at the start of the

https://mc06.manuscriptcentral.com/cgj-pubs
current loading cycle.

This model is capable of approximating the \( p-y \) relationship for clay recommended by Matlock (1970) or API (2000) by adjusting the input parameters, including \( c, \ n \) and \( C_d \). The input parameter \( p_{ult} \) is based upon the equations given by API (2000):

\[
(3) \quad p_{ult} = \left( 3 + \frac{y'z}{s_u} + \frac{lz}{D} \right) s_w \text{ for } z < X_R
\]

\[
(4) \quad p_{ult} = 9s_w \text{ for } z \geq X_R
\]

where \( D \) is the pile diameter; \( s_u \) is the undrained shear strength; \( \gamma' \) is the average effective unit weight; \( z \) is the depth below the ground surface; \( J \) is a dimensionless empirical constant, which is 0.5 for soft clay and 0.25 for medium clay; and \( X_R = \frac{6D}{s_u + \gamma'z} \geq 2.5D \) is the depth from the ground surface to the bottom of the reduced resistance zone.

The Boulanger model can be flexibly used to model different \( p-y \) backbone curves. The model is written in C++ and incorporated in the OpenSees program (Mazzoni et al. 2007) being developed by the PEER Center. But in the Boulanger model, the soil strength degradation is not taken into account. Therefore, the ultimate lateral capacity \( p_{ult} \) keeps constant under cyclic loads. For this reason, a cyclic strength degradation model, which is a function of accumulated absolute plastic displacement is presented in the following section and incorporated in the Boulanger model.

**Cyclic degradation model**

Based on the cyclic T-bar and ball tests, Einav and Randolph (2005) developed a soil
strength degradation model, in which the current shear strength is assumed to depend on the accumulated absolute plastic shear strain $\xi$, using the following expression:

$$\frac{s_u}{s_{u,\text{initial}}} = \delta_{\text{rem}} + (1 - \delta_{\text{rem}})e^{-\frac{3\xi}{\xi_{95}}}$$  

(5)

where $s_u$ and $s_{u,\text{initial}}$ are the current shear strength and initial shear strength of the soil, respectively. $\delta_{\text{rem}}$ is the fully remolded strength ratio calculated by inverting the sensitivity of the soil. $\xi_{95}$ represents the cumulative shear strain required for 95% remolding.

In the cyclic penetrometer tests, the data that can be measured include the number of cycles, the penetration and extraction displacement, and the soil resistance. But it is difficult to measure the soil strain. In light of this fact, the current shear strength of the soil is assumed to depend on the accumulated absolute plastic displacement in current study. Similar to Eq. (5), a shear strength degradation model based on plastic displacement is described as:

$$\frac{s_u}{s_{u,\text{initial}}} = \delta_{\text{rem}} + (1 - \delta_{\text{rem}})e^{-\frac{y_{pa}}{D_t}}$$  

(6)

where, $s_{u,\text{initial}}$ at a certain depth can be measured during the initial penetration of a T-bar penetrometer, and calculated by dividing the net T-bar penetration resistance $q_t$ by a constant bearing factor $N_{kt} = 10.5$, which was recommended by Martin and Randolph (2006). $D_t$ is the T-bar diameter, $\alpha$ is the damage factor fitted with T-bar test data, and $y_{pa}$ is the accumulated absolute plastic displacement of soil element that can be measured. Since the initial undrained shear strength $s_{u,\text{initial}}$ is measured
during the first push of T-bar, from when the degradation model takes effect afterwards, the plastic displacement should be accumulated from the end of the first penetration of T-bar.

In order to study the relation of the accumulated plastic displacement and the total displacement in a T-bar test, cyclic movement of T-bar in homogeneous soil is simulated with a $p$-$y$ element developed by Boulanger et al. (1999) in this paper. As there is no gap forming during the cyclic movement of full-flow penetrometer, the displacement of the soil has only two components: the plastic displacement $y_p$ and elastic displacement $y_e$. The plastic displacement $y_p$ can be expressed as the sum of displacement of plastic spring and gap spring in the Boulanger model. Fig. 1 presents the evolution of the total displacement $y$ and the plastic displacement $y_p$ by modeling T-bar tests at different displacement amplitudes $y_a$. Correspondingly, comparisons between the accumulated absolute plastic displacement $y_{p\alpha}$ and the accumulated absolute total displacement $y_{t\alpha}$ are made in Fig. 2 and Fig. 3. It can be observed that $y_{p\alpha}$ is very close to $y_{t\alpha}$ for the cyclic T-bar penetration with a displacement amplitude $y_a$ exceeding one diameter or more. Therefore, this paper argues that $y_{p\alpha}$ can be replaced with $y_{t\alpha}$ for the T-bar test with a cyclic range exceeding one diameter, which is sufficient to meet the requirements of fitting the damage factor with the accumulated absolute displacement of T-bar.

This study assumes that the maximum width of damage influence zone is two diameters of T-bar, and the center line of the damage influence zone is identical with
that of the cyclic movement zone, as shown in Fig. 4, where the horizontal axis indicates the normalized time and $T$ is the cycle period. Hodder et al. (2009) also made the similar assumption for determining the damage influence zone of cyclic T-bar tests. Therefore, the accumulated absolute plastic displacement $y_{pa}$ should only be calculated in the range of the damage influence zone.

Based on the above discussion, this study argues that the accumulated absolute plastic displacement for cyclic T-bar tests with displacement amplitudes over one diameter can be described by the following equation:

\[
(7) \quad y_{pa} = 4ND_t
\]

where $N$ is the number of T-bar penetration and extraction cycles. The equation indicates that the accumulated absolute plastic displacement is approximately equal to the accumulated absolute total displacement in the assumed damage influence zone. This is due to that the elastic displacement is very small and can be neglected with respect to the plastic displacement when the displacement amplitude exceeds one diameter. Zhang et al. (2010) made the same assumption for estimating the accumulated absolute plastic displacement of T-bar.

For cyclic T-bar tests at a certain depth, $\alpha$ can be obtained by fitting the soil strength degradation curve with Eq. (6) and (7). In order to examine the applicability of the cyclic degradation model, four groups of T-bar penetration data are fitted. Table 1 summaries the details of the relevant data given by Sahdi (2013), Hodder et al. (2009)
and Boylan et al. (2007). These fitted curves are presented in Fig. 5, which correlate well with the experimental data.

**Improved p-y curve model**

The effect of soil softening under cyclic loading is not taken into account in the existing Boulanger model (Boulanger et al. 1999). Therefore, this study combines Boulanger model with the above cyclic degradation model. Rather than a constant, the ultimate lateral capacity $p_{ult}$ is a variable that depends on the accumulated absolute plastic displacement of the soil element. The improved p-y curve model updates $p_{ult}$ at every time step by the following equation:

$$p_{ult} = N_p s_u = N_p s_u,\text{initial} \left( \delta_{rem} + (1-\delta_{rem})e^{-\frac{\gamma p a}{D}} \right)$$

where $N_p$ is the bearing capacity factor.

It has been argued that the lateral p-y curve provided by API (2000) underestimates the ultimate lateral capacity of soft soil and the proposed value of $N_p$ is conservative (Jeanjean 2009; Zhang et al. 2010). Based on centrifuge test results and finite element analysis, Jeanjean (2009) modified an empirical function proposed by Murff and Hamilton (1993) for the calculation of $N_p$, and the equation was presented as follows:

$$N_p = N_1 - N_2 e^{-\frac{\xi \lambda}{D}}$$

where $N_1$ is the limiting value at depth, $(N_1 - N_2)$ is the intercept at the soil surface ($N_1 = 12, N_2 = 4$ for the smooth pile). The parameter $\xi$ is taken to be a linear function of $\lambda$, which is described by
(10) $\xi = 0.25 + 0.05\lambda$, $\lambda < 6$

(11) $\xi = 0.55$, $\lambda \geq 6$

(12) $\lambda = \frac{s_{u0}}{s_{u1}D}$

where $s_{u0}$ is the shear strength intercept at the soil surface, $s_{u1}$ is the linear rate of increase of strength with depth. Jeanjean’s (2009) empirical equations are adopted in this paper to simulate the cyclic lateral responses of pile.

This study modifies the OpenSees code (Mazzoni et al. 2007) by applying the improved $p$-$y$ curve model to analyze the cyclic loading response of a shaft. In this subsection, the cyclic $p$-$y$ curves of the single soil element considering the effect of soil softening are simulated at different displacement amplitudes $y_a$ and load amplitudes $p_a$. The simulation is based on the improved and original $p$-$y$ curve model, respectively. The parameters of the soil element and pile are given in Table 2. Fig. 6 presents that the soil strength decreases cycle by cycle due to the accumulation of the plastic displacement in the improved $p$-$y$ curve model, while the cyclic $p$-$y$ curves modeled by the original $p$-$y$ curve model indicate that the soil strength keeps constant. Fig. 6 (d) indicates that for the improved $p$-$y$ curve model, the degradation rate of the ultimate lateral capacity declines gradually with the number of cycles increasing, and tends to remain steady after a number of cycles. Fig. 6 also shows that the larger the displacement amplitude $y_a$ is, the faster the degradation rate is. This is due to the fact
that the enlarged displacement amplitude leads to the rapid growth of the accumulated plastic displacement, which worsens the degradation of the soil strength. In comparison, the variation of the displacement amplitude has no impact on the soil strength in the original \( p-y \) curve model. Fig. 7 (a) and (b) present that when the cyclic load of a fixed amplitude \( p_a \) acts on a soil element, the maximum displacement per cycle extends with the number of cycles for the improved \( p-y \) curve model, because the soil strength is further mobilized by enlarging displacement of soil spring to make up for the degradation of soil strength. In comparison, the maximum displacement per cycle keeps constant for the original \( p-y \) curve model. Fig. 7 (c) displays that the soil element only performs the elastic behavior for the cyclic loading with smaller amplitude, which results in a constant maximum displacement. Fig. 7 (a) and (d) indicate that, for the load amplitude \( p_a = 0.75p_{ult0} \), the cyclic analysis stops when the ultimate lateral capacity \( p_{ult} \) reduces to \( 0.75p_{ult0} \), because the soil resistance cannot increase to the load amplitude by enlarging the displacement.

**Practical operation procedure**

In order to model the lateral response of single pile under cyclic loading based on the improved \( p-y \) curve model, this paper proposes a practical operation procedure, as illustrated in Fig. 8. The practical operation procedure has three steps:

- The data of soil strength degrading with displacement at different depths can be obtained by cyclic T-bar penetration tests;
- The parameters of the cyclic degradation model can be obtained by fitting the
T-bar tests data;

- The load-displacement curves of the pile connected to a series of soil springs can be simulated by the improved $p$-$y$ curve model.

**Case study**

A case study is conducted to validate the applicability of the improved $p$-$y$ curve model. A full scale testing program was reported in Zhang et al. (2010), which involved a series of centrifuge model tests of the lateral response of a fixed-head single rigid pile in soft clay. The soil conditions are characterized by cyclic T-bar penetration tests. The damage coefficient $\alpha$ of the proposed cyclic degradation model is obtained by fitting their degradation curve of cyclic T-bar test in this study. Then, the load-displacement curve of the single rigid pile is simulated based on the improved $p$-$y$ curve model.

**Parameter fitting based on cyclic degradation model**

Zhang et al. (2010) conducted the centrifuge model tests at a centrifuge acceleration of 50 g along the centerline of a strongbox in the beam centrifuge at the University of Western Australia (UWA). The characteristics of pile and soil are summarized in Table 3. The T-bar tests were carried out using a T-bar with a diameter of 5 mm (0.25 m at prototype scale, for the test acceleration of 50 g). The sensitivity of the soil is approximately 2.5, so the fully remolded strength ratio $\delta_{\text{rem}}$ is 0.4. The T-bar penetration resistance during the test is shown in Fig. 9. By fitting cyclic T-bar data based on the proposed cyclic degradation model and the assumption of calculating $y_{\text{pa}}$, the estimated damage factor $\alpha$ is 0.268. The fitted degradation curve is presented in Fig.
Validation of the improved p-y curve model

Two-way cyclic lateral loading tests were carried out on a hollow circular aluminum tube with an outer diameter of 12 mm (0.6 m in prototype scale), a wall thickness of 1 mm (0.05 m in prototype scale), a total length of 90 mm (4.5 m in prototype scale), and a embedment depth of 60 mm (3 m in prototype scale) (Zhang et al. 2010). Cyclic pile tests were conducted under displacement control of pile head. The measured shear strength profile was expressed by an approximate exponential form: 

\[ s_u = 2.2 + 3.3z^{0.9} \]

The empirical equations (9) ~ (12) proposed by Jeanjean (2009) are adopted to estimate the bearing capacity factor \( N_p \). The depth of the bottom of the reduced resistance zone \( X_R \) can be calculated by the equation recommended by API (2000), and the coefficient of drag force \( C_d \) increases linearly from 0.1 to 1 with depth in the reduced resistance zone.

Fig. 11 compares the calculated cyclic p-y curve with the experimental results of Zhang et al. (2010). The lateral load of pile head \( H \) is normalized by the product of the projected vertical area \( LD = 1.8 \text{ m}^2 \), and the average shear strength \( s_{u,av} = 6.75 \text{ kPa} \) over the depth of embedment. The horizontal displacement \( y_m \) in the middle of the pile is normalized by the pile diameter \( D \). Due to the lack of the T-bar tests data and that the sensitivities of the soil at different depths in the centrifuge are approximately identical, a vertical array of soil elements adjacent to the pile are assumed to have the same the damage factor \( \alpha = 0.268 \). In fact, owing to the complexity of soil layers in the field,
the damage factors should vary with the depth. As shown in Fig. 11, the calculated results correlate well with the experimental data by setting the coefficients \( c = 2.5 \) and \( n = 1 \). This study argues that it is necessary to modify three key coefficients that control the maximum drag force, the tangent module of the plastic spring and the curve sharpness, respectively, for simulating the load-displacement curves of the rigid pile.

**Performance examination of model**

In order to further examine the performance of the improved model, the normalized load-displacement curve of pile at a fixed displacement amplitude is modeled. The parameters of soil-pile model are identical to those for the above case. In Fig. 12, \( y_h \) is the displacement of the pile head. The normalized pile head load at a given displacement amplitude declines as the further cyclic movement of pile due to the degradation of soil strength caused by the growing accumulated plastic displacement. Moreover, the normalized cyclic \( p-y \) curves of the soil elements connected to pile elements at different depths are displayed in Fig. 13. It can be found that the displacement amplitudes of soil springs decreases with the increasing depth, and the corresponding degradation rates decline gradually due to the reduction of the accumulated plastic displacement per cycle. It can also be observed that the gap effect is more obvious for the upper soil layers. Fig. 13 (d) presents that there is no the formation of gap when the displacement amplitude is relatively smaller.

**Conclusion**

A cyclic degradation model based on the accumulated absolute plastic displacement
is proposed to investigate the damage mechanism of soil strength in this study. By incorporating the cyclic degradation model into the Boulanger model, an improved $p$-$y$ curve model based on T-bar tests data is developed to study the response of laterally loaded piles subjected to cyclic loading. Analyses show that the accumulated plastic displacement of the penetrometer in a cyclic range of two diameters is sufficient to approximate the accumulated displacement. The damage influence zone in the cyclic movement of T-bar is also assumed to be cyclic range of two diameters for calculation of the accumulated absolute plastic displacement. This study argues that the plastic displacement beyond the damage influence zone has only little impact on the soil strength in concerned location. This study embeds the improved $p$-$y$ curve model into the OpenSees program (Mazzoni et al. 2007) to simulate cyclic $p$-$y$ curves. It is convenient and low-cost calculation for simulating cyclic lateral response of pile based on the OpenSees platform. The improved $p$-$y$ curve model is proved to be very efficient to present the soil strength degradation by modeling the cyclic lateral responses of soil element and pile. In the case study, the excellent agreement between the theoretical predictions and the measured data shows the practicability of the proposed model. It is revealed that the simulation of the load-displacement curves of a single pile is controlled by the comprehensive influence of three coefficients. This study suggests that for the purpose of obtaining the damage factor of the proposed cyclic degradation model, the cyclic displacement amplitude should be at least one diameter in T-bar penetration tests for geological exploration. By considering the effect of soil strength
degradation, the lateral response of a single pile under cyclic loading can be more precisely predicted by the proposed model.

Acknowledgment

Financial support from the National Natural Science Foundation of China (Grant Nos. 51179201) and the Fundamental Research Funds for the Central Universities is gratefully acknowledged.

References


API 2000. Recommended practice for planning, designing and constructing fixed offshore platforms–working stress design, American Petroleum Institute, Washington, D.C.


Society of Civil Engineers, New York, pp. 600-619.


Figure captions

Fig. 1. Evolution of total displacement and plastic displacement in the simulation of T-bar tests with different displacement amplitudes

Fig. 2. Evolution of accumulated absolute total displacement and plastic displacement of T-bar: (a) $y_a = D_t$; (b) $y_a = 0.5D_t$; (c) $y_a = 0.1D_t$

Fig. 3. Proportion of the accumulated plastic displacement at different displacement amplitudes (the number of cycles is 10)

Fig. 4. Damage influence zone

Fig. 5. Cyclic degradation model comparison against experimental data: (a), (b) data from Sahdi (2013); (c) data from Hodder et al. (2009); (d) data from Boylan et al. (2007)

Fig. 6. Comparison of normalized cyclic $p-y$ curves at different displacement amplitudes: (a) $y_a = 0.25D$; (b) $y_a = 0.5D$; (c) $y_a = 0.75D$; (d) degradation of the ultimate lateral capacity

Fig. 7. Comparison of normalized cyclic $p-y$ curves at different load amplitudes: (a) $p_a = 0.75p_{ult0}$; (b) $p_a = 0.5p_{ult0}$; (c) $p_a = 0.25p_{ult0}$; (d) degradation of the ultimate lateral capacity

Fig. 8. Practical operation procedure

Fig. 9. Cyclic T-bar penetrometer test

Fig. 10. Cyclic degradation model comparison against experimental data

Fig. 11. Comparison of computed and experimental normalized load-displacement
curves of rigid pile

**Fig. 12.** Normalized load-displacement curve of rigid pile at a fixed displacement amplitude

**Fig. 13.** Normalized cyclic $p$-$y$ curves of soil elements at different depths: (a) at soil surface; (b) depth = $1.25D$; (c) depth = $2.5D$; (d) depth = $3.75D$
Table 1. T-bar penetration data and fitted results.

<table>
<thead>
<tr>
<th>Data sources</th>
<th>Depth (m)</th>
<th>$D_t$ (m)</th>
<th>$S_t$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sahdi (2013)</td>
<td>2.05</td>
<td>0.25</td>
<td>2.2</td>
<td>0.288</td>
</tr>
<tr>
<td>Sahdi (2013)</td>
<td>3.8</td>
<td>0.5</td>
<td>2.3</td>
<td>0.275</td>
</tr>
<tr>
<td>Hodder et al. (2009)</td>
<td>2.375</td>
<td>0.25</td>
<td>2.38</td>
<td>0.307</td>
</tr>
<tr>
<td>Boylan et al. (2007)</td>
<td>3.5</td>
<td>0.04</td>
<td>5</td>
<td>0.288</td>
</tr>
</tbody>
</table>
Table 2. Parameters of soil element and pile.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial ultimate lateral capacity of soil (kPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil sensitivity</td>
<td>$S_t$</td>
<td>2.5</td>
</tr>
<tr>
<td>Strain at which 50% of the soil strength is mobilized in a compression test</td>
<td>$\varepsilon_{50}$</td>
<td>0.01</td>
</tr>
<tr>
<td>Pile diameter (m)</td>
<td>$D$</td>
<td>0.25</td>
</tr>
<tr>
<td>Damage factor</td>
<td>$\alpha$</td>
<td>0.3</td>
</tr>
<tr>
<td>Coefficient of drag force</td>
<td>$C_d$</td>
<td>1</td>
</tr>
<tr>
<td>Coefficient that controls tangent module of the plastic spring</td>
<td>$n$</td>
<td>5</td>
</tr>
<tr>
<td>Coefficient that controls curve sharpness</td>
<td>$c$</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 3. Parameters of soil-pile model.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (kPa)</td>
<td>$s_u$</td>
<td>$2.2 + 3.3z^{0.9}$</td>
</tr>
<tr>
<td>Soil sensitivity</td>
<td>$S_t$</td>
<td>2.5</td>
</tr>
<tr>
<td>Strain at which 50% of the soil strength is mobilized in a compression test</td>
<td>$\varepsilon_{50}$</td>
<td>0.01</td>
</tr>
<tr>
<td>Pile diameter (m)</td>
<td>$D$</td>
<td>0.6</td>
</tr>
<tr>
<td>Total length of pile (m)</td>
<td>$L_t$</td>
<td>4.5</td>
</tr>
<tr>
<td>Embedment length of pile (m)</td>
<td>$L$</td>
<td>3</td>
</tr>
<tr>
<td>Damage factor</td>
<td>$\alpha$</td>
<td>0.268</td>
</tr>
<tr>
<td>Bearing capacity factor</td>
<td>$N_p$</td>
<td>$12 - 4e^{-0.51z}$</td>
</tr>
<tr>
<td>Coefficient of drag force</td>
<td>$C_d$</td>
<td>$0.3z + 0.1$</td>
</tr>
<tr>
<td>Coefficient that controls tangent module of the plastic spring</td>
<td>$n$</td>
<td>1</td>
</tr>
<tr>
<td>Coefficient that controls curve sharpness</td>
<td>$c$</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Fig. 1. The evolution of total displacement and plastic displacement in the simulation of T-bar tests with different displacement amplitudes.
Fig. 2. Evolution of accumulated absolute total displacement and plastic displacement of T-bar: (a) $y_a = D_1$; (b) $y_a = 0.5D_1$; (c) $y_a = 0.1D_1$.
Fig. 3. Proportion of the accumulated plastic displacement at different displacement amplitudes (the number of cycles is 10)
Fig. 4. Damage influence zone
Fig. 5. Cyclic degradation model comparison against experimental data: (a), (b) data from Sahdi (2013); (c) data from Hodder et al. (2009); (d) data from Boylan et al. (2007).
Fig. 6. Comparison of normalized cyclic p-y curves at different displacement amplitudes: (a) $y_a = 0.25D$; (b) $y_a = 0.5D$; (c) $y_a = 0.75D$; (d) degradation of the ultimate lateral capacity
Fig. 7. Comparison of normalized cyclic p-y curves at different load amplitudes: (a) $p_a = 0.75p_{ult0}$; (b) $p_a = 0.5p_{ult0}$; (c) $p_a = 0.25p_{ult0}$; (d) degradation of the ultimate lateral capacity.
Fig. 8. Practical operation procedure
Fig. 9. Cyclic T-bar penetrometer test
Fig. 10. Cyclic degradation model comparison against experimental...
Fig. 11. Comparison of computed and experimental normalized load-displacement curves of rigid pile.
Fig. 12. Normalized load-displacement curve of rigid pile at a fixed displacement amplitude.
Fig. 13. Normalized cyclic p-y curves of soil elements at different depths: (a) at soil surface; (b) depth = 1.25D; (c) depth = 2.5D; (d) depth = 3.75D