Surface Roughness Effects on the Bearing Capacity of Piles in Dry Sand

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ABSTRACT
In order to delineate effects of surface roughness on the unit shaft resistance of piles embedded in a dry natural fine sand mass, a research program comprising 25 axial loading tests was carried out on 44 mm diameter model piles with different surface roughness. In order to provide piles with different surface roughness they were wrapped with sandpapers with different grits. The results indicate that when the average abrasive particles size of sandpapers varies from 18.3 to 425 microns, the lateral earth pressure coefficient increases from 0.95 to 1.75. This implies that pile surface roughness enhances the tendency of the sand to dilate during loading, which increases magnitude of the radial effective stress against the pile surface. Also, it was disclosed that when the average abrasive particles size of sandpapers varies from 18.3 to 425 microns, the unit shaft resistance increases from 2.5 to 9.1 kPa. These results indicate that the pile shaft resistance increases due partially to the fact that the sand mass-sand paper interface friction angle increases as the sand paper roughness increases. However, it also depends on the rise of radial effective stress due to dilation of sand during loading.

KEYWORDS: pile, surface roughness, shaft resistance, sandpaper, sand

INTRODUCTION
Bearing of large loads is the first aim to enhance the load bearing capacity of a pile since structural loads should be transmitted to ground anyway. In sorely loads when bed layer is not suitable, one should use either very costly expense massive piles or modern methods in design and construction of a pile. Thus, economic considerations and inability in use of massive piles
with large diameter due to site limitations should be considered. The numbers of parameters that influence performance of a pile subjected to an axial load are wide and mostly interrelated. Leland and Kraft (1991) categorized these parameters in 4 main parameters: installation methods, load, soil and pile parameters. An equation of the following form is usually used to estimate the ultimate skin resistance of a vertical circular pile in sand:

\[
\tau_f = \sigma'_{rf} \tan \delta_f = K \sigma_v \tan \delta_f
\]  

(1)

Where \( \sigma'_{rf} \) is the radial effective stress at failure, \( \delta_f \) is the pile-sand friction angle at failure and \( K \) is an earth pressure coefficient. Parameters \( K \) and \( \delta_f \) are the most important ones that need to be determined. Using direct shear test data, Kulhawy et al. (1983) related the friction angle \( \delta_f \) to the internal friction angle of sand \( \phi \) for different construction materials. Vesic (1977) stated that \( \tan \delta_f \) could be taken as “\( \tan \phi \), the coefficient of friction of the remolded soil in term of effective stress”. Several studies have been performed on the shear resistance at the interface between soil and foundation material (Potyondy 1961; Yoshimi and Khishida 1981; Acar et al. 1982; Bozozuk et al. 1979; Datta et al. 1980). These data suggest that for a steel pile a \( \delta_{\phi'\sigma} \) ratio of about 0.7 is reasonable for siliceous sand, whereas a \( \delta_{\phi'\sigma} \) ratio of about 0.6 may be more appropriate for calcareous sands. Uesugi and Khishida (1986) concluded that the steel–sand friction angle, \( D_{50}\) of sand and sand type had significant influence on the coefficient of friction at yield. However, influence of test type, uniformity coefficient \( C_u \), and normal stress would not significantly affect the coefficient of friction at yield. The lateral earth pressure coefficient \( K \) is the most difficult term to evaluate. Construction procedure and pile loading may cause the \( K \) value to decrease or increase from the original \( k_0 \) value. Reviewing current literature reveals that the reported \( K \) values vary over a wide range from \( K_a \) to \( K_p \) and in some cases, may be higher than \( K_p \) (where \( K_a \) and \( K_p \) are Rankine’s active and passive earth pressure coefficients, respectively). The procedure in the American Petroleum Institute (API 1984) RP 2A code recommends the use of \( K \) values equal to 0.8 and 1.0 to estimate shaft resistance of open and close-end driven piles in sand, respectively. Using 64 pullout tests on rough and smooth piles, Alawneh et al. (1999) indicated that pile placement method, initial sand condition, pile surface roughness, and pile end type are factors affecting the ultimate uplift shaft resistance of single pile installed in dry sand. The research program of Lehane et al. (1993) led to the conclusion that the radial effective stress acting on the pile shaft comprises two components. These are stationary radial effective stress component, in other words radial stress after installation and before loading, and the additional component which may arise during loading:

\[
\sigma'_{rf} = \sigma'_{rc} + \Delta \sigma'_r
\]  

(2)

Changes in \( \sigma'_r \) during pile loading may be divided in two components due to the principle stress rotation \( \Delta \sigma'_{rp} \) in the sand and the dilation due to slip at the interface \( \Delta \sigma'_{rd} \):

\[
\Delta \sigma'_r = \Delta \sigma'_{rp} + \Delta \sigma'_{rd}
\]  

(3)

It is pointed out that the principal stress rotations associate with pile loading causes the reduction in \( \sigma'_r \). Laboratory studies of Symes in sand (1983) suggest that sensitivity to principal stress rotation decreases with increasing relative density. Following an initial reduction, a marked increase in \( \sigma'_r \) was observed as each section of the pile approached local failure. Laboratory studies of sand to steel shear by Usugi and Kishida (1986) have shown that the shear and volume
strains developed between peak and ultimate conditions are concentrated in a narrow band of soil close to the interface. For surfaces with roughness of typical steel piles, this dilation consists of a few grains close to the shaft moving radially so that slip may occur. As indicated by Boulon and Foray (1986), the radial stress change resulting from a boundary displacement of $\delta h$ applied to an elastic soil mass of shear stiffness $G$ is given by:

$$\Delta \sigma'_{rd} = 2\delta h \frac{G}{R}$$

(4)

This expression suggests that $\Delta \sigma'_{rd}$ decreases sharply with radius and vice versa. Considering of Lehane (1993) studies Equation (1) may be written in the following form:

$$\sigma'_r = \sigma'_v[K_m(z) + \frac{\Delta \sigma'_r}{\sigma'_v}]$$

(5)

where $K_m$ is an earth pressure coefficient excluding the contribution of sand dilation and the principle stress rotation, $\sigma'_v$ is the effective vertical stress, and $z$ is the depth below ground surface. This equation can be written as

$$\sigma'_r = K(z)\sigma'_v$$

(6-a)

$$K(z) = [K_m(z) + \frac{\Delta \sigma'_r}{\sigma'_v}]$$

(6-b)

Where $K$ is the lateral earth pressure coefficient including the contribution of sand dilation and the principle stress rotation.

In the current work in order to investigating the effects of surface roughness on the unit shaft resistance, a research program comprising 25 loading tests was carried out on 44 mm diameter model piles, with different surface roughness, embedded in dry natural fine sand.

PROCEDURE

Sand container

An apparatus incorporating a sand container was designed and constructed. The sand container was 0.358 m$^3$ in volume and 60 cm in height with an octagonal horizontal cross section with a 98 cm diameter circumferential circle. The container was made of 4 mm thick steel plate strengthened with stiffeners. To eliminate the effect of end bearing capacity resistance of piles, end of each pile was extruded through a hole at the base of the container. The container was designed large enough so as the circumferential circle radius exceeds the extent far beyond the zone of primary compaction around the pile in sand which has been reported by Robinsky and Morrison(1964) and Broms(1966); and therefore the effect of lateral boundaries of container could be ignored. The sand container and view of the hole at its base are presented in Figure 1.
Steel pipes with 42.5mm in outside diameter, 2.5mm in wall thickness and 750mm in length were employed as model piles. Each pile shaft surface could be covered with the defined sandpaper and installed in the container, while its lower end would be extruded through the base hole. Accordingly the sand-pile shaft interface would be 600mm in depth and overall diameter of each pile wrapped with sandpaper was 44 mm. A sophisticated loading cap which was pinpointed at its center was mounted on the embedded pile head and load was applied through the loading system to the center of this cap.

In order to provide piles with different surface roughness they were wrapped with sandpapers with different grits. Grit defines number of abrasive particles per inch of sandpaper. Thus, the lower the grit, the higher the distance and height of abrasive particles and vise versa. Consequently, roughness increases as grit decreases. Characteristics of used sandpapers and their applications are summarized in Table 1. In this research the average abrasive particle size represents pile shaft surface roughness.
Table 1: Characteristics of used sandpapers and their applications

<table>
<thead>
<tr>
<th>Sandpaper Grit</th>
<th>Common Name</th>
<th>Average abrasive particle size (microns)</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Coarse</td>
<td>425</td>
<td>Heavy sanding and stripping, roughing up the surface</td>
</tr>
<tr>
<td>60</td>
<td>Coarse</td>
<td>269</td>
<td>Smoothing of the surface, removing smaller imperfections and marks.</td>
</tr>
<tr>
<td>80</td>
<td>Medium</td>
<td>201</td>
<td>Final sanding pass before finishing the wood</td>
</tr>
<tr>
<td>100</td>
<td>Medium</td>
<td>162</td>
<td>Removing dust spots or marks between finish coats</td>
</tr>
<tr>
<td>120</td>
<td>Fine</td>
<td>125</td>
<td>Fine sanding of the finish to remove some luster or surface blemishes and scratches</td>
</tr>
<tr>
<td>180</td>
<td>Fine</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>Extra Fine</td>
<td>52.2 ± 2.0</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Super Fine</td>
<td>35.0±1.5</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>Super Fine</td>
<td>18.3±1.0</td>
<td></td>
</tr>
</tbody>
</table>

Test sand

Silicate sand with grain-size distribution curve as shown in Figure 2 was used. It was a poorly graded fine sand SP with curvature coefficient $C_c$, uniformity coefficient $C_u$, effective size $D_{50}$ and solid particles specific gravity $G_s$ as 1.0, 1.82, 0.29 and 2.60, respectively. Furthermore its maximum and minimum dry densities were determined to be 17.5 and 15.1 kN/m$^3$, respectively. However, the average dry density that was achieved by gradual filling of the container through a constant height sand raining apparatus was 16.6 kN/m$^3$, corresponding to $D_e = 65\%$. The internal friction angle of the sand, obtained using direct shear test at stress levels similar to those would encountered in the sand container, was 38.6°.

In order to determining the sand mass-sandpaper interface friction angle special direct shear tests were performed using different sandpapers. At first a piece of hard wood block was fitted into the lower platen of a 10 × 10 cm direct shear apparatus shear box. Then the selected sandpaper was glued onto its surface. The total thickness of the wooden block and sandpaper was so as the finished surface of sandpaper and upper surface of the lover platen of the shear box were exactly on same plane, where the shear plane passes through. This was a precise and time consuming job, however. These are shown in Figure 3. Then the upper platen was mounted and filled with test sand and compacted to achieve $γ_d (av) = 1.66 \text{ gr/cm}^3$. Finally the appropriate normal stress was applied and the shear test was performed. In Figure 4 variations of average abrasive particle size versus interface friction angle is shown. It is seen that the higher the average abrasive particle size the larger the interface friction angle, however this relation is not linear.
Figure 2: Grain-size distribution curve of sand used in this study

Figure 3: Sandpaper and placing method in direct shear device
INSTALLATION PROCEDURE OF PILE IN THE CONTAINER

After setting the pile in the container and extruding its end through the base an adjusting system comprising three fixing bars, as shown in Figure 5, was used. After filling the container with sand this system could be removed and then the loading system was mounted on the top of the pile shaft. In order to prevent the pile to settle due to its own weight a screw support, as shown in Figure 6, was employed. This support of course was removed after first loading step.

Figure 4: Variations of average abrasive particle size versus interface friction angle

Figure 5: Support system of the pile
LOADING SYSTEM AND TEST PROCEDURE

In engineering practice, piles may be loaded in compression, uplift, lateral or combination of these modes. This work, however, focuses on the axial loading using direct surcharge method, while a load cell could measure the applied load magnitude. For applying axial load to the pile a loading system comprising a loading frame and lever was designed. The load cell and loading lever connection was a simple ball point hinge. After filling the container, in order to monitoring the pile settlement a rigid glass plate was improvised at the pile head and four displacement transducers (LVDT) were installed symmetrically at its corners. The records of these LVDTs were averaged and adopted as pile vertical displacement. Having set up the system, pile loading was carried on with 10N incremental steps and the pile was permitted to settle unscrewing the pile support that was placed beneath the container. Each step being held until the rate of settlement descended to zero. Although the settlements were mostly quick and instantaneous, however, each loading step maintained 300 second for more confidence. At each step pile settlement was monitored and records were plotted. This procedure was repeated for all tests. In these tests, loading level was increased step by step until the soil failed and the pile settled rapidly. For further reliability, each test was repeated and the results were averaged. The complete system is shown in Figure 7.
TEST RESULTS AND DISCUSSION

The test results are summarized in Table 2. In this table the average unit shaft resistance, $f_a$, and the lateral earth pressure coefficient $K$ values are calculated from the following equations:

\[
    f_a = \frac{Q}{A_s} \quad \text{(7)}
\]

\[
    K = \frac{2f_a}{L\gamma' \tan \delta_f} \quad \text{(8)}
\]

where $Q$ is ultimate load, $A_s$ is embedded pile surface area, $L$ is embedded pile length and $\gamma'$ is effective unit weight of soil. Also, $\delta_f$ is interface friction angle at failure which was obtained from direct shear test and the results were shown in Figure 4.
Table 2: Summary of test results

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Sandpaper Grit</th>
<th>Average abrasive particle size ($\mu$m)</th>
<th>δf</th>
<th>Ultimate Load (kgf)</th>
<th>Average Unit Shaft Resistance (kPa)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>18.3 ± 1</td>
<td>27.9</td>
<td>22.348</td>
<td>2.70</td>
<td>1.02</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>18.3 ± 1</td>
<td>27.9</td>
<td>18.260</td>
<td>2.20</td>
<td>0.83</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>18.3 ± 1</td>
<td>27.9</td>
<td>23.196</td>
<td>2.80</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>18.3 ± 1</td>
<td>27.9</td>
<td>19.057</td>
<td>2.30</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>35 ± 1.5</td>
<td>31.3</td>
<td>31.728</td>
<td>3.83</td>
<td>1.26</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>35 ± 1.5</td>
<td>31.3</td>
<td>29.773</td>
<td>3.59</td>
<td>1.19</td>
</tr>
<tr>
<td>7</td>
<td>400</td>
<td>35 ± 1.5</td>
<td>31.3</td>
<td>30.232</td>
<td>3.65</td>
<td>1.21</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>35 ± 1.5</td>
<td>31.3</td>
<td>28.209</td>
<td>3.4</td>
<td>1.12</td>
</tr>
<tr>
<td>9</td>
<td>280</td>
<td>52.2 ± 2</td>
<td>32</td>
<td>29.215</td>
<td>3.52</td>
<td>1.13</td>
</tr>
<tr>
<td>10</td>
<td>280</td>
<td>52.2 ± 2</td>
<td>32</td>
<td>31.208</td>
<td>3.76</td>
<td>1.21</td>
</tr>
<tr>
<td>11</td>
<td>180</td>
<td>82</td>
<td>32.8</td>
<td>36.735</td>
<td>4.43</td>
<td>1.38</td>
</tr>
<tr>
<td>12</td>
<td>180</td>
<td>82</td>
<td>32.8</td>
<td>28.858</td>
<td>3.48</td>
<td>1.08</td>
</tr>
<tr>
<td>13</td>
<td>180</td>
<td>82</td>
<td>32.8</td>
<td>30.353</td>
<td>3.66</td>
<td>1.14</td>
</tr>
<tr>
<td>14</td>
<td>120</td>
<td>125</td>
<td>35.1</td>
<td>38.815</td>
<td>4.68</td>
<td>1.34</td>
</tr>
<tr>
<td>15</td>
<td>120</td>
<td>125</td>
<td>35.1</td>
<td>35.427</td>
<td>4.27</td>
<td>1.22</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>162</td>
<td>37</td>
<td>40.715</td>
<td>4.91</td>
<td>1.31</td>
</tr>
<tr>
<td>17</td>
<td>100</td>
<td>162</td>
<td>37</td>
<td>34.594</td>
<td>4.17</td>
<td>1.11</td>
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<tr>
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<td>5.04</td>
<td>1.34</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>162</td>
<td>37</td>
<td>43.778</td>
<td>5.28</td>
<td>1.41</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>201</td>
<td>39.4</td>
<td>44.213</td>
<td>5.33</td>
<td>1.30</td>
</tr>
<tr>
<td>21</td>
<td>80</td>
<td>201</td>
<td>39.4</td>
<td>45.730</td>
<td>5.51</td>
<td>1.35</td>
</tr>
<tr>
<td>22</td>
<td>60</td>
<td>269</td>
<td>42.1</td>
<td>58.477</td>
<td>7.05</td>
<td>1.57</td>
</tr>
<tr>
<td>23</td>
<td>60</td>
<td>269</td>
<td>42.1</td>
<td>53.980</td>
<td>6.51</td>
<td>1.45</td>
</tr>
<tr>
<td>24</td>
<td>40</td>
<td>425</td>
<td>46.3</td>
<td>77.340</td>
<td>9.33</td>
<td>1.79</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
<td>425</td>
<td>46.3</td>
<td>73.648</td>
<td>8.88</td>
<td>1.70</td>
</tr>
</tbody>
</table>

To compare the test results, the average unit shaft resistance-displacement curves for all sandpapers are presented in Figure 8. It is observed that when the average abrasive particles size of sandpaper varies from 18.3 to 425 microns, the average unit shaft resistance increases from 2.5 to 9.1 kPa. It is seen that the curves plotted in Figure 8 are of a general pattern as shown in Figure 9. This pattern comprises three main regions AB, BC and CD. In most tests, up to point A, that includes elastic displacement, variations of surface roughness slightly affect the shaft resistance and the resistance due to increase of roughness is mobilized after this point has been achieved. In zone AB elasto-plastic behavior dominates. Furthermore in this zone a linear relation between shaft resistance and displacement of pile may be adopted. From point B up to point C behavior becomes nonlinear. At point C flow process manifests itself and then develops. Finally at point D soil surrounding the pile fails and the pile settles rapidly.
In the middle of elasto-plastic zone AB, for a defined increase of stress rate, the pile settlement rate decreases as the surface roughness increases and causes the shaft resistance to increases. The sandpaper-ambient soil interface mechanism is presented schematically in Figure 10. It is seen that when surface of pile is rougher, dimensions a and b increase and consequently
interlocking between pile and soil increases. Thus the load required to overcome the surface resistance due to interlocking, increases and thus the rate of pile settlement decreases as the surface roughness increases. As the load is increased the interface soil dilates due to shear strain grow. This, in turn, increases lateral stress and causes the shaft resistance to increase. It seems that as settlement proceeds due to load increment the specific volume of the sand intimate to the pile surface finally reaches to its critical state and then the pile settles rapidly. The pile settlement value corresponding to the pile ultimate capacity due to shaft resistance is more or less identical for all tests and is 9 ~ 10% of pile diameter.

![Diagram of pile surface and soil interface](image)

**Figure 10:** Pile surface and soil interface

The results shown in Figure 8 can be normalized as shown in Figure 11. In this Figure, P and $P_u$ are shaft resistance at each stage and at ultimate resistance, respectively. Also, S and $S_u$ are displacement at each stage and at ultimate displacement (9 to 10% of pile diameter), respectively. Furthermore, $\delta_f$ and K are the interface friction angle at failure and lateral earth pressure coefficient, respectively.
The curve of average unit shaft resistance obtained from tests versus average abrasive particle size which is representative of the roughness, is shown in Figure 12. It is observed that the relation between average abrasive particle size (roughness) and average unit shaft resistance is acceptably linear. Moreover the curve of average unit shaft resistance obtained from these tests versus interface friction angle at failure $\delta_f$ is shown in Figure 13.
Figure 13: Variations of average unit shaft resistance against interface friction angle at failure

Values of lateral earth pressure coefficient which are obtained from equation (8), versus average abrasive particle size are shown in Figure 14. It is concluded that when average abrasive particles size of sandpapers varies from 18.3 to 425 microns, the average lateral earth pressure coefficient $K$ increases from 0.95 to 1.75. This phenomenon is attributed to the sandpaper roughness effect on the interface soil dilation. It may be concluded that the higher the pile surface roughness the higher the load bearing capacity due to sand dilation. As seen in Figure 14, the highest $K$ value belongs to the most rough pile surface. This observation is generally in agreement with the following formula (Jardine et al., 1998):

$$\sigma'_{rd} = \frac{GR_{cla}}{R}$$

In which $\sigma'_{rd}$ is the change in radial effective stress during pile loading, $R_{cla}$ is the centerline average roughness, $G$ is the operating shear modulus, and $R$ is the pile radius.
CONCLUSIONS

A research program comprising 25 loading tests was carried out on 44 mm diameter model piles with different surface roughness, embedded in dry natural fine sand. It was disclosed that:

General pattern of average unit shaft resistance variations against pile displacement is identical in all tests.

Pile settlement corresponding to the ultimate capacity due to shaft resistance is 9 to 10% of pile diameter in all tests.

Average unit shaft resistance increases as the surface roughness is increased. However, test results indicate that the pile shaft resistance increases due partially to the fact that the sand mass-sandpaper interface friction angle increases as the sandpaper roughness increases. However, it also depends on the rise of radial effective stress due to dilation of surrounding sand during loading.

Lateral earth pressure coefficient increases as surface roughness is increased. This implies that pile surface roughness enhances the tendency of the sand to dilate during loading, which, in turn, increases the magnitude of the radial effective stress against the pile surface.

It should be mentioned that separation of effect of each of two parameters, interface friction angle and lateral earth pressure coefficient, is not possible. As they both arise from interlocking between soil and pile surface and mutually affect each other.
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