Surface roughness effects on the shaft resistance of piles in dry sand

Les effects de la rugosité de la surface des piles sur la capacité de leur port dans le sable sec

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ABSTRACT
In order to delineate 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 mass. In all tests the loading level was increased until the soil failed. The results obtained from this study indicate 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. Also, the 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.

RÉSUMÉ
Pour étudier les effets de la rugosité de la surface des piles sur la résistance moyenne de la paroi de la pile dans le sable sec, un programme de recherche composé de 25 tests de chargement est fait sur les modèles de laboratoire des piles à 44 mm de diamètre mais à la surface de différentes rugosités. Dans tous les tests, le chargement est accru jusqu`a ce que le sol soit rompu. Les tests ont démontré sol soit rompu. Les tests ont démontré que l`augmentation de la rugosité entraîne d`une part l`augmentation de la tendance du sable à la dilatation et de l`autre l'augmentation de la tension radiale efficace au moment du chargement. Aussi, les tests ont démontré que la résistance de la paroi de la pile se produit par la croissance de l`angle du frottement interne entre la pile et le sol avec l`augmentation la rugosité et en même temps avec la croissance de la tension radiale efficace provenant de la dilatation du sable au moment du chargement.

Keywords : pile, surface roughness, shaft resistance, sand paper, sand

1 INTRODUCTION

The numbers of parameters influencing performance of a pile subjected to an axial load are wide and mostly interrelated. Leland and Kraft(1991) categorized these parameters in 4 main classes: 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:

$$\tau_f = \sigma'_{rf} \tan\delta_f = K\sigma'_v \tan\delta_f \tag{1}$$

Where τ_f is the ultimate skin resistance of pile, σ'_{rf} is the redial effective stress at failure, δ_f is the pile-sand friction angle at failure and K is the earth pressure coefficient. Parameters K and δ_f are the most important ones that need to be determined. The research program of Lehane et al (1993) leaded to the conclusion that the radial effective stress acting on the pile shaft comprises of two components. These are stationary radial effective stress component, in other words radial stress after installation and before loading σ'_{rc}, and the additional component which may arise during loading $\Delta\sigma'_r$. Changes in σ'_r during pile loading may be split in two components due to the principle stress rotation $\Delta\sigma'_{rp}$ in the sand and the dilation due to slip at the interface $\Delta\sigma'_{rd}$. In the current work in order to investigate 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.

2 PROCEDURE

2.1 *Sand container*

A rigid hexagonal steel box 0.8m side and 0.6m high, was employed as sand container. To eliminate the effect of end bearing capacity resistance of piles, end of each pile was extruded through a hole, 4.6cm in diameter, at the base of the container. The container was designed large enough so as its circumferential circle radius exceeded the extent of the zone of primary compaction around a cylindrical pile in sand which has been reported by Robinsky and Morrison(1964) and Broms(1966). Therefore the effect of lateral boundaries of container could be ignored.

2.2 *Model piles*

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 a defined sand paper 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 sand paper was 44mm . Having filled the container with sand a sophisticated loading cap was mounted on the pile head. Axial loading was carried out with a well instrumented loading system.

In this study in order to provide piles with different surface roughness they were wrapped with sandpapers with different

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grits. Grit defines number of abrasive particles per inch of a 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 are summarized in Table1. In this research the average abrasive particle size represents pile shaft surface roughness.

2.3 *Test sand*

In this study Silicate sand 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 the maximum and minimum dry densities were determined to be 17.5 and 15.1kN/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 $D_r \approx 65\%$. The internal friction angle of the sand, obtained from direct shear test at stress levels similar to those would be encountered in the sand container, was 38.6°. For different sand mass-sandpapers, the interface friction angles were determined by performing direct shear tests at normal stress levels comparable to those in the sand container. The results of interface friction angles obtained from direct shear tests also are summarized in Table1.

Table 1. Characteristics of used sandpapers and Sand mass-sandpaper interface friction angle δ_f.

Test No	Sand paper Grit	Average particle size (microns)	δ_f Degrees
1	40	425	46.3
2	60	269	42.1
3	80	201	39.4
4	100	162	37.1
5	120	125	35
6	180	82	32.8
7	280	52.2±2.0	32
8	400	35.0±1.5	31.3
9	1000	18.3±1.0	27.9

3 INSTALLATION PROCEDURE OF THE PILE IN THE CONTAINER

After setting the pile in the container and extruding its end through the container base an adjustable system comprising three fixing bars 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 was employed.

4 LOADING SYSTEM AND TEST PROCEDURE

For applying axial load to the pile a loading system comprising a loading frame and lever was designed. After filling the container, the soil surface was flattened and evened deliberately with a straight edge and then four displacement transducers (LVDT) were installed symmetrically at four sides of the pile head. Then an axial load cell was positioned between pile cap and loading lever. The load cell and loading lever connection was a simple ball point hinge. The whole system is shown in Figure 1. Then the pile was loaded with a defined weight that was hanged on the lever arm and the pile was permitted to settle unscrewing the pile support that was placed beneath the container. Loading level was increased step by step until the soil failed and the pile settled rapidly. At each step pile settlement was monitored and records were plotted. This procedure was repeated for piles covered with different sandpapers. For further reliability, each test was repeated and the results were averaged.

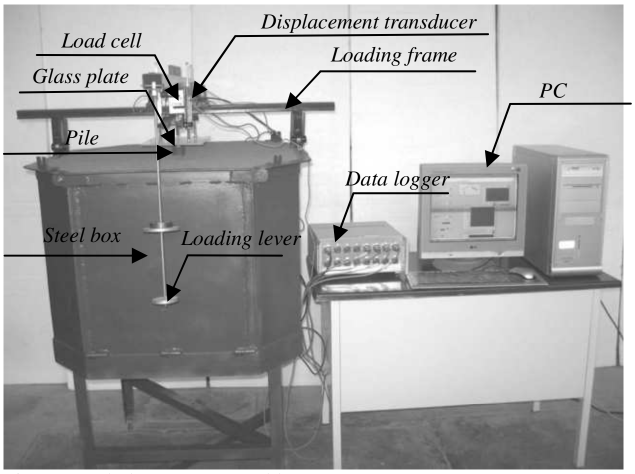

Figure 1. Whole system assembly

5 TEST RESULTS

In order to delineate effects of surface roughness on the unit shaft resistance, a research program comprising 25 loading tests was carried out. In order to compare the test results, the average unit shaft resistance-displacement curves for all sandpapers are presented in Figure 2.

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 2 are of a general pattern as shown in Figure 3.

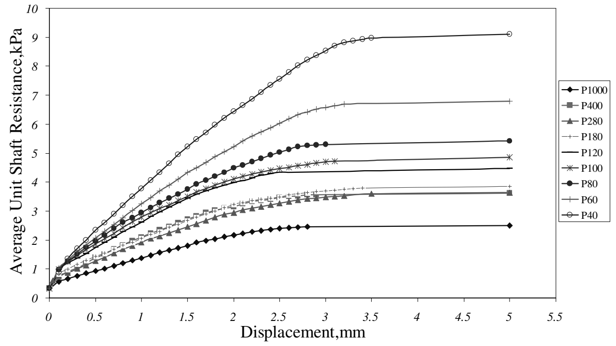

Figure 2. The average unit shaft resistance-displacement curves for all sandpaper

This pattern comprises three main regions AB, BC and CD. In most tests, up to point A, that elastic behavior is the part of it, variations of surface roughness slightly affect shaft resistance of pile and the resistance due to increase of roughness is mobilized after this point has been achieved.

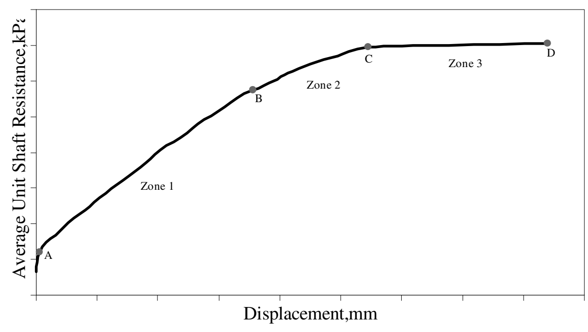

Figure 3. General pattern of test results

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. The pile settlement at ultimate capacity due to shaft resistance is more or less same for all tests and is 9 ~ 10% of pile diameter. At the middle of elasto-plastic zone AB, for a definite increase of stress rate, the pile settlement rate decreases as the surface roughness increases and causes the shaft resistance to increases. It is observed that when surface of a pile is rougher the 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 development. 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 sand close to the pile surface finally reaches to its critical state and then the pile settles rapidly.

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 4. Moreover the curve of average unit shaft resistance obtained from tests versus interface friction angle at failure δ_f is shown in Figure 5.

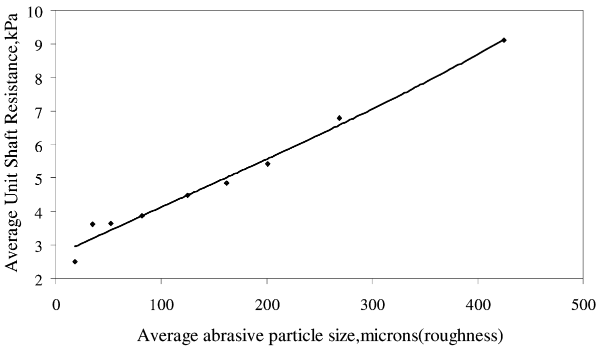

Figure 4. Variations of average unit shaft resistance against average abrasive particle size(roughness)

Values of lateral earth pressure coefficient versus average abrasive particle size are shown in Figure 6. The lateral earth pressure coefficient is calculated from the following equation:

$$K = \frac{2Q}{A_S L \gamma' \tan \delta_f} \quad (2)$$

Where Q is the ultimate load, A_s is the embedded pile surface area and γ' is the effective unit weight of the soil. Also, δ_f is the interface friction angle at failure which was obtained from direct shear test and results are summarized in Table 1.

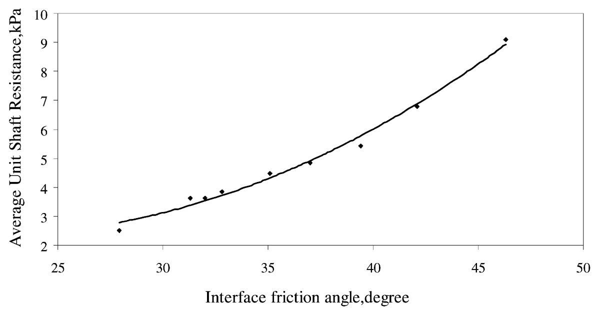

Figure 5. Variations of average unit shaft resistance against interface friction angle at failure

It is concluded that when average abrasive particle 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 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 6, 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):

$$\sigma'_{rd} \propto \frac{G R_{cla}}{R} \quad (3)$$

In which σ'_{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.

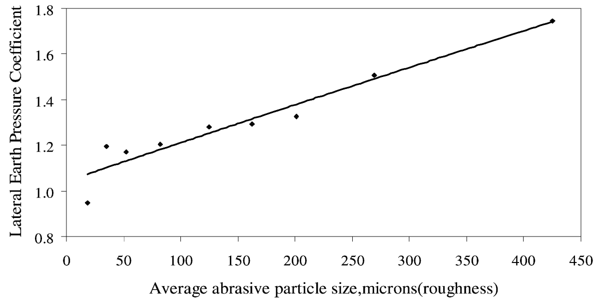

Figure 6. Variations of lateral earth pressure coefficient against average abrasive particle size

Equation 1 and the results indicate that pile shaft resistance increases due partially to the fact that the sand mass-sandpaper 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 pile loading. The variations of average shaft resistance obtained from tests against lateral earth coefficient changes and also variations of average shaft resistance versus tangent of interface friction angle at failure are shown in Figures 7 and 8, respectively. 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.

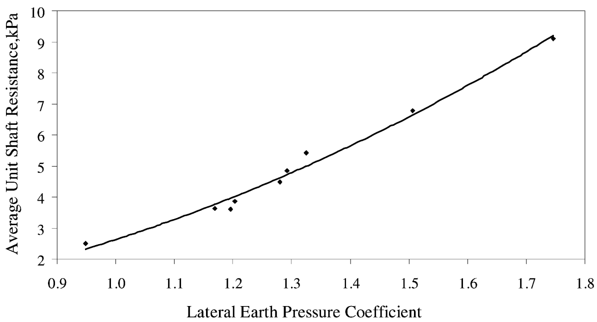

Figure 7. Variations of lateral earth pressure coefficient against average unit shaft resistance

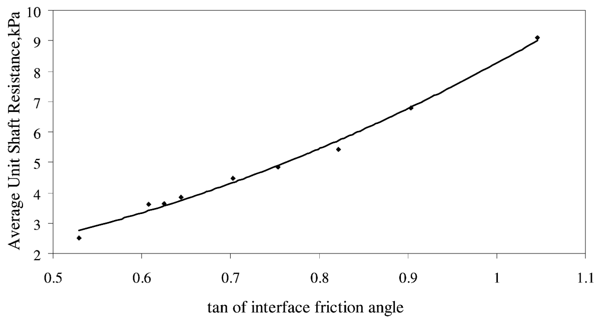

Figure 8. Variations of tangent of interface friction angle versus average unit shaft resistance

6 CONCLUSIONS

In this study in order to obtain 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. It was disclosed that:

(1) Increment and general pattern of average unit shaft resistance–displacement curves are identical in all tests.

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

(3) Average 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 sand paper roughness increases. However, it also depends on the rise of radial effective stress due to dilation of surrounding sand during loading.

(4) Lateral earth 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.

(5) 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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