ABSTRACT: Soft clay is consolidated upon any slight change in the effective vertical stress. Consolidation causes a downdrag movement to the shaft piles that penetrate this layer. The downdrag movement adds additional loads to the already loaded pile. This force is expressed as a negative skin friction. Negative skin friction extends to a depth depending on the consolidating soil-pile interaction. This depth is referred to as the neutral plan.

This paper presents a study on the behavior of soil-pile interaction during soil consolidation. Experimental work was developed to analyze the negative skin friction and the location of the neutral plane on a single pile embedded in soft clay layer. The pile is ended either in clay or sand soil, or is floated. The clay layer was allowed to consolidate. The study concluded that the neutral plane is located closer to the end of the pile as the end bearing increases. The depth of neutral plane increases by increasing the embedded length of the pile in the clay layer. Closed form equations of Shong, 2002, predict the experimental results in very well agreement.


Cet article présente une étude sur le comportement de l’interaction sol-pieux lors de la consolidation des sols. Un travail expérimental a été développé pour analyser le frottement négatif et l’emplacement du plan neutre sur un seul pieu foncé dans une couche d’argile. La couche d’argile peut se consolider. L’étude montre que le plan neutre se situe près de l’extrémité du pieu ou la charge augmente. Ainsi, la profondeur du plan neutre augmente en même temps que la longueur du pieu. Ces résultats sont en accord avec ceux de Shong, 2002.

KEYWORDS: soft clay consolidation, pile foundation, negative skin friction, down drag movement neutral plane, floating piles
Shong approach is adapted in the analysis of the results in this study. This paper represents a study to investigate the behavior of soil-pile interaction during soil consolidation. Since full-scale testing of the influence of the large number of variables involved is economically unreasonable, a simulated laboratory experiment has been designated. A special rig was designed and constructed for this purpose. In order to carry out the investigations, experimental program was developed.

2 EXPERIMENTAL WORK

(Nasser 2010) arranged the experimental rig as shown in Figure 1. Three P.V.C circular model piles with different diameters of 1.5, 2 and 2.5 cm were chosen to model the pile in this study. Compression tests were carried out on a specimen of this P.V.C pipes to determine its modulus of elasticity. The modulus of elasticity of the pile material; P.V.C is 1500000 KN/m³. The surface of the pile is smooth.

![The experimental rig](image)

Fig. 1 The experimental rig

Two layers of sand with depth 5cm for each layer. One of these layers placed on the surface of soft soil and the second layer under the soil.

Bentonite soil has been adapted for the experimental investigation in this study. 85% water content provides a soft consistency of bentonite. For this condition initial void ratio is 2.38, bulk density is 16 KN/m³.

A surcharge has to be applied to the soil layer for consolidation. Steel and lead plates of 1.2kN total weight were arranged for the surcharge. These loads simulate a surcharge of 1m fill of unit weight 17kN/m³.

The vertical displacement of the model pile and the soil surface were measured using dial gauges. The displacement of the model pile is measured at its center. The soil settlement is measured at a point located at the mid distance between the pile shaft and the container wall.

Strain gauges are fixed at various depths of the length of the pile to measure the strains occurred on the pile during soil consolidation. Number and locations of the strain gauges are designed depending on the thickness of the clay layer.

Table (1) illustrates the experimental program. Three cases of boundary conditions were considered in this study. The first case is the pile ended in the clay layer. This represents clay end bearing case. The second case is the pile ended in the sand layer. And the last case represents floating pile. That is, the pile passes through the lower plate and not resting on any soil. This case is aimed to investigate the pure shaft resistance without the interference of the end condition.

![Table (1) Different cases with code for each test](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Cases</th>
<th>Pile Diameter (cm)</th>
<th>L/d</th>
<th>Pile Length (cm)</th>
<th>Code</th>
<th>No. of Strain gages</th>
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<tbody>
<tr>
<td>1</td>
<td>CASE I (end bearing clay EC)</td>
<td>1.5</td>
<td>10</td>
<td>15</td>
<td>L15EC</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>CASE I (end bearing sand ES)</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>L30EC</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>CASE II (end bearing clay EC)</td>
<td>2</td>
<td>10</td>
<td>20</td>
<td>L20EC</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>CASE II (end bearing sand ES)</td>
<td>15</td>
<td>30</td>
<td>40</td>
<td>L40EC</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>CASE III (end bearing clay EC)</td>
<td>2.5</td>
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<td>L25EC</td>
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<tr>
<td>6</td>
<td>CASE III (end bearing sand ES)</td>
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<td>37.5</td>
<td>L37EC</td>
<td>4</td>
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<tr>
<td>7</td>
<td>Floating (F)</td>
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<td>15</td>
<td>10</td>
<td>L15ES</td>
<td>3</td>
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<tr>
<td>8</td>
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</tbody>
</table>

3 RESULTS AND ANALYSIS

3.1 Time–strain behavior of pile model

Figures 2 shows the axial strain with time of applying the surcharge, for pile model (L22.5Ec). From the Figure, it can be seen that the top strain is higher and occurs earlier than the middle and the bottom strains. However, it declines just after reaching the early peak. The other strains continue increasing until the end of the test.

![Fig. 2 Time-Axial strain curves of pile model (L22.5Ec)](image)
than the initial one. The bottom strain is much less than the upper and middle ones. The stress increase, and hence the water dissipation and the soil consolidation, is moderate at the bottom strain compared with the other two locations.

Figure 3 illustrates the pile strains for pile model (L22.5Ec). It can be seen from the Figure that the bottom strains are generally larger when compared with the previous case of pile ended in clay. This can be attributed to the increased dissipation of pore water pressure through the bottom layer. Moreover, sand layers offer resistance to the pile movement; end bearing. This increases stresses in the bottom portion of the pile. Hence, there is increase in the monitored strain.

Figure 4 shows the pile strains for pile model (L25F). Here, the boundary condition at the pile tip does not allow for developing stresses at the bottom of the clay layer. Hence, the bottom strains are the least among all locations along the pile.

3.2 Distribution of normal strain and shear stress along the normalized depth of the pile

Figure 5 depicts the distribution of normal strain and shear stress along the normalized depth of the pile models (L15EC and L15ES). The shown strains are those monitored at the end of the test. As can be seen from the Figure, small values of strains are indicated in the upper part where the excess pore pressure had dissipated, and hence, consolidation process had decayed. The axial strain increases by the presence of a sand layer at the pile tip (case II). Strain increases until it reaches a peak value at an intermediate depth. Then, it decreases. Strain decrease reflects a decrease in the dragging force. That is the developing of positive shear resistance along the pile shaft. Hence, the zone of the peak strain is a transition zone from negative skin friction to positive skin friction. Obviously, the neutral plan is located at this peak point.

The developed shear stress along the pile shaft is calculated from the monitored strain. Shear stress starts from zero value at the surface of the soil and increases until it reaches a peak negative value at an intermediate depth, then it decreases down to zero at the elevation of the neutral plane where the positive skin friction develops. Neutral plane is determined where shear stress changes from negative to positive. That is at the intersection of the curve with the vertical axis. As can be seen from the Figure the location of the neutral plane is matched from these two approaches.

As can be seen from Figure 5, the transition of pile ended in clay is located near to the middle of the pile. The transition zone of pile ended in sand is located near the pile toe. The neutral plane is located at the peak point of the transition zone. In addition, it can be seen that the normalized neutral depth is (0.53) and (0.61) for the cases of end bearing on clay and sand, respectively. That is the neutral plane is located closer to the end of the pile as the base layer gets stiffer.

This observation can be explained based on the simple equilibrium of vertical forces. (Accumulative negative skin friction = accumulative positive skin friction + bearing resistance). Since small-bearing resistance is available for case I, positive skin friction should be large enough to resist negative skin friction. Hence, negative skin friction will be reduced with the neutral plane being located further from the pile tip.

3.3 Effect of the pile length embedded in the clay layer on the location of neutral plane

Figure 6 illustrates the normalized neutral depth as a function to the pile length embedded in the clay layer. The pile diameter is 1.5cm. Two cases; I, and II of tested piles are shown in the Figure. As can be seen
from the Figure, the normalized neutral depth increases with the
increase of the pile length embedded in the clay layer.

The explanation of the effect of the pile length on the neutral plane is
due to the compressibility of the pile length. When negative skin
friction is induced in a short pile, most of the downdrag is transmitted to
the pile tip in the form of penetration to the bearing layer. Whereas, for
long pile the downdrag is partly taken by the pile compressibility, and
partly transmitted to the tip.

3.4 Determination of the Neutral Plane

Shong approach is adapted to locate the neutral plan. This
approach is outlined in Section 1. The factor of safety of pile
capacity against ultimate pile capacity, Fs is considered two, and β is taken 0.3.

![Fig. 7 Monitored and Calculated Location of the Neutral Plane](image)

Figure 7 depicts the normalized neutral depth from both the
monitored data and Shong approach. The pile diameter is
1.5cm. Two cases; I, and II, of tested pile are shown in the
Figure. As can be seen from the Figure, the calculated
normalized neutral depth is having the same trend as the
monitored ones. The approach results into very good agreement
with the normalized neutral depth.

4 CONCLUSION

This paper presents a study on the behavior of pile during soil
consolidation. In order to carry out the investigations,
experimental program was designated. A special rig was
designed and constructed for this purpose. Based on test results
the following conclusions are reached:

- Consolidation of the soil surrounding the pile due to
  surcharge loads induces negative skin friction on piles.
- The monitored strains along the pile length reflect the
  consolidation process with time. Strain increases from the
  pile top until it reaches a peak value at the location of the
  neutral plane.
- Sand layers, at the pile tip, offer resistance to the pile
  movement; end bearing. This increases stresses in the
  bottom portion of the pile. Hence, there is increase in the
  monitored strain, when compared with piles ended in clay,
  or floated.
- Shear stress is initiated from zero value at the surface of the
  soil and increases until it reaches a peak negative value at
  an intermediate depth. Then, it decreases down to zero at
  the elevation of the neutral plane where the positive skin
  friction develops.
- The neutral plane is located closer to the end of the pile as
  the base layer getting stiffer.
- The normalized neutral depth increases with the increase of
  the pile length.
- Shong approach for ND results into very good agreement with the
  monitored ones.

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