Laboratory Experiment of Soil Vertical Displacement Measurement Near an Axially Loaded Pile

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Abstract. The paper presents the results of static pile load test in laboratory conditions with additional measurement of vertical displacement of soil surrounding the shallow embedded pile. The main purpose of research to determine the pattern of soil displacement due to axial load of the pile. Although, the dimensions of pile are strongly differing from field pile used in practice, there are some phenomena which are similar to natural conditions. Tests were performed on a small precast concrete pile which was 7 cm in diameter and 25 cm long embedded in cohesionless soil. The measurements of the study were: applied load, resistance under the toe of the pile, settlement of the pile and vertical displacement of chosen points in the soil near to the toe of the pile. Performed test indicated that in small load the displacement in soil increase due to increasing load, but when the load was approaching the value of ultimate load, displacement stopped and at the limit load the direction of displacement vector changed to upward. The shape of the shear failure mechanism took the form of a logarithmic spiral which was widely described in literature. In this study an attempt at mathematical description has been made. In the proposed approach it was assumed that the displacement of the pile influenced the change of the sphere volume under the pile base which affects the displacement of the selected points of the soil. The research allowed to determine the size of ground space which was affected by the studied pile. The other studies indicate that the failure mechanism in deep piles and poorly compacted soils is caused by punching shear failure when only soil displacement down occurs, but in very compacted sands the mechanism of failure would be similar to obtained in laboratory test.

1. Introduction

Transferring the axial load from the pile head to the surrounding soil is still a subject of many studies. Pile load capacity is a sum of skin friction and toe resistance. The mechanism of the resistances mobilization is completely differing. Toe resistance is a result of soil compression below the pile. Skin friction is a result of deflection of soil layer surround the shaft of the pile. Skin friction at failure is the result of friction between soils grains and skin of the pile, or sometimes shear strength close to the piles skin. Very important issue is the mobilization of the resistances with settlement of the pile. In practice the basic verification of pile load capacity is static pile load test. The result of the test is settlement curve. Settlement of the pile induce the displacement of soil. The previous research [1], [2] indicated that there is relationship between skin friction and toe resistance which should not be neglected in calculation and pile load capacity prediction. The relationship causes that mechanism of soil deformation near to the toe of the pile is not an obvious issue. Therefore, experimental studies were carried out. Measurement of soil displacement around the pile was described by White and Bolton [3], [4] which used PIV image.
analysis to detect the soil deformation during installation of a displacement pile. In their presented papers load the sphere of load transfer could be divided on two parts: 1: with horizontal compression and vertical extension which occurs on the sides of the toe of the pile; 2: with horizontal extension and vertical compression which occurs directly under the toe of the pile. In deep piles the deformation of soil was generally caused by soil contractive behaviour which was widely described by Han and Salgado [5] and Lashkari [6].

In presented paper the results of laboratory research were presented. Test were performed on a small precast concrete pile which was 7 cm in diameter and 25 cm long embedded in cohesionless soil. Author realizes that in presented laboratory tests the scale effect is important, so the results of the research could not be directly related to the piles used in practice. However, it should be pointed out that the test is carried out on natural materials, where the laws of soil mechanics are also applied. Laboratory test is characterized by high precision and could be carried out in homogeneous soil. Therefore, the phenomena investigated in laboratory condition are valuable because they could be difficult or impossible to detect in field.

2. Laboratory test procedure

The laboratory stand consists of steel chamber, sand, concrete piles, and measuring apparatus. The chamber was filled by medium sand layer by layer. Each layer was compacted using steel plate. During filling the chamber soil density have been controlled. The conditions in the chamber were roughly homogeneous.

![Figure 1. Laboratory stand pile no 1: a) general scheme of stand, b) head of the pile and telescopic relays, c) prepared stand with displacement and force sensors.](image)
The soil was previously tested, and geotechnical parameters have been determined. In the test concrete pile was used. Vertical displacements of soil were measured by telescopic relays. Pile and telescopic vertical relays were placed during filling the chamber. Dimensions of the stand was presented in figure 1. More about preparation of the stand has been described also in [7].

In the laboratory research five test have been carried out. In the paper only three of them are presented. In table 1 the soil conditions in the chamber and ultimate load of pile were presented. Test no 1 and 3 were investigated approximately similar soil density, the last one in higher density. The investigated points in each test were differ. The positions of points were in horizontal range 3-5 cm from the pile and 0-15 cm below the toe of the pile. The load was measured using load cell in range 0-50 kN placed at the head of the pile. Both the settlement of the head of the pile and points in soil were measured using optoelectronic displacement four sensors in range 0-50 mm, and resolution 0.005 mm.

| Pile number | porosity index $e$ [-] | water content $w$ [%] | Ultimate load $N_{gr,2}$ [kN] |
|-------------|------------------------|------------------------|-------------------------------|
| 1           | 0.65                   | 4.41                   | 3.6                           |
| 3           | 0.65                   | 4.35                   | 3.2                           |
| 4           | 0.63                   | 4.21                   | 6.0                           |

Tests were carried out 1-3 days after preparation the stand. Pile was axially loaded in steps of load. In each step of load, the settlement of the pile and displacement of the chosen points in soil were measured. The results of the test were: stabilized settlement of pile’s head and vertical displacement of
soil. Measurements of example pile was presented in figure 2. The heavier the load the longer the stabilization process. In further calculation the most important data concerned the last findings in each step of load.

3. Results

The results of soil were applied load $N_2$, settlement of the pile $s_p$ and vertical displacements of the chosen points near to the toe of the pile $s_2$, $s_3$, $s_4$. The figure 3 presents the position of the investigated points in soil. The graphs in figure 3 present settlement curve obtained from static pile load tests. The graphs at the very bottom of figure 3 present relationship between applied load and vertical displacement of the points. The displacement in soil had the same direction as settlement of the pile but significantly lower values. It was caused by radial displacement from the base of the pile. Furthermore, the settlement of the pile is transferred from the base to the sphere of soil which had larger side surface than area of the pile base.

![Figure 3. Results of laboratory test of three piles. Negative displacement in upward direction.](image)

In the first steps of load the settlement was approximately in linear relationship to applied load and they were generally in downward direction. The displacement of some points decreased in subsequent steps of load. Finally, the points which were the closest to the toe of the pile they were started to move
upward. At the same stage of load, the settlement curve began to bend significantly. The phenomena indicated the beginning of the failure mechanism.

Vertical displacement of soil of the investigated pile no 1 were initially constant. The test was carried out in very low density of soil. It could cause a soil compression of soil in the sphere which was smaller than the distance from the base to investigated points. At failure extrusion of soil was observed. The higher displacements were induced in point \( s_3 \) which was deeper than \( s_2 \). This indicated the formation of soil sphere which the centre was below the pile base.

The soil extrusion which was observed at failure was not noticed at the surface of the ground, so the failure mechanism is more similar to piles than to shallow foundation.

4. Mathematical description

Calculated displacement of the soil was made based on cavity expansion assumptions. The soil moved by the toe of the pile cause decrease of soil volume below the pile which was caused by compressibility of soil. Furthermore, the soil pushed by the pile cause an increase of volume the sphere which was surrounds the pile and can be compared to the sphere. In the presented analyse it was assumed half of the settlement cause soil movement and half is only compressibility. It depends of critical value of porosity index, but for the purposes of the analysis presented a simplification was made.

Changes in volume in soil below the pile was cause by settlement of the pile’s base. It could be described by equation (1).

\[
\Delta V = 0.25 \pi D^2 s_p
\]  

Where: \( D \) – diameter of the pile [m], \( s_p \) – settlement of the pile [m].

The sphere of displacement soil induced by settlement of the pile and bordered by investigated point in soil had a radius \( R_p \). The volume changes can be described as (2).

\[
\Delta V = \frac{2}{3} \pi \left( R_k^3 - R_p^3 \right)
\]

Where: \( R_k = R_p + u; u \) – radial displacement of soil on the surface of studied sphere [mm].

Initial radius as a distance between \( j \)-point in soil and top of the cone under the pile (which was described also in figure 6) can be calculated from equation (3).

\[
R_p = \sqrt{x_j^2 + (z_j - \alpha s_p)^2}
\]

Where: \( x_j \) – horizontal distance between the pile axis at \( j \)-point; \( z_j \) – vertical distance between pile base and at \( j \)-point in soil; \( \alpha \) – coefficient of forming shear cone below the pile assumed in test as 0.1D.

From the (1-2) the equation (4) was obtained.

\[
u^3 + 6R_p u^2 + 6R_p^2 u - 0.75D^2 s_p = 0
\]  

It was assumed that the centre of the mobilized soil sphere moved due to settlement of the pile and at the settlement corresponding to the failure the sphere achieved maximum dimensions. The vertical displacement of soil can be calculated from (5).
\[ u_v = s_j = u \sin \left( \arctan \left( \frac{x_j - s_p}{s_j} \right) \right) \] (5)

Where: \( s_j \) – vertical displacement of \( j \)-point.

The presented method was validated with measured vertical displacement of soil near to the toe of pile no 3. The results were consistent. The highest displacement appeared in a middle depth point in soil. This proved the concentration of displacement in this place. At the settlement of the pile higher than 10 millimetres the displacement of the point \( s_3 \) began to stop.

![Figure 4. Displacement of chosen points in soil due to settlement of the pile no 3.](image)

The equations (3-4) allowed to determine the deflection of lines below the pile according to settlement of the pile. The results of calculation were presented in figure 4.

![Figure 5. Calculated vertical displacement of soil on the chosen level below the pile and in horizontal distance from the pile from 0,3-2,5D. D-diameter of the pile. Lines presented on the graph are the settlement of the pile \( s_p \) in millimetres.](image)

The displacement of soil presented on figure 5 indicate that the zone of significant displacement reached up to 1D at the depth 1D below the pile, and approximately 2D at the depth 2D below the pile base. The displacements of calculated line depended on settlement of the pile. In the figure 4 deflection line of soil according settlement of the pile 2,6,10 and 12 mm was presented. This is due to assumed a spherical soil displacement zone under the pile. Near to the toe of the pile a local extrusion was observed at settlement of the pile 12 mm. It could be also noticed that at the depth equals 2D the higher settlement of the pile induced higher displacement of soil, but the displacement slowed down at high settlement of
pile. At the settlement of the pile equal to 12 mm there were no significant differences could be seen. It was caused by the beginning of the failure mechanism. The investigated phenomena could be explained by three phases of load presented in figure 6.

In the phases presented in Figure 6 the blue lines point out the main directions of soil displacement. The presented lines are logarithmic spirals presented also in Terzaghi, Meyerhof theory [8]–[11]. Small axial load of the pile (Phase 1) caused generally downward displacement of soil. In the phase the soil is generally compacted. The center of the sphere is placed at the piles toe. The second phase is observed in range of load which are usually used in practice. Under the pile’s toe a soil cone is formed which move the soil to downward and also on sides. The center of the zone is located at the top of the cone. The last third phase is the soil displacement at failure. At the phase the dimensions of the sphere are constant. There is also upward displacement observed which is typical to extrusion of soil. The phenomena is common known in shallow foundation but it could also observed in piles where soil is in dilative state [12].

5. Conclusions
The main objective of the study was the determine of displacement zone in soil induced by settlement of the pile. Laboratory test indicated that the sphere of the soil which interacted with pile had a width roughly in range from 2D to 3D at failure. At failure the soil displacement was distributed radially from the centre of the created soil sphere bellow the pile. It indicated that a part of soil at the level of pile base was pushed to upward direction. The vertical upward direction displacement of soil which was observed in small load of pile could change the state of stress and cause an increase with horizontal stresses in soil above the pile base. It could be an explanation of high skin friction. However, it should be kept in mind that the phenomena might not apply for deep piles where soil is in high geostatic stress and has a contractive behaviour – not dilated.
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