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Effect of soil compaction around driven pile and prediction of pile settlement on claystones

Effet du compactage du sol autour du pieu battu et les prévisions de l'affaissement du pieu sur les argilites

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ABSTRACT: In the article the problem of geotechnical application of claystone as a base of driven pile foundations has been considered. When using these foundations a compaction zone is formed in the soil space around the driven pile. The purpose of this research is to analyze the influence of compaction zones on the results of numerical calculations for predicting the settlement of a driven pile on claystones. The following tasks were solved: 1) The existing investigations of pile settlement in clays were analyzed; 2) The characteristics of experimental sites and methods for testing single field piles on claystones were described; 3) Calculation of single pile settlement was performed carried out by numerical methods with the use of Plaxis 3D software package; 4) The experimental data were compared with the results of calculations by numerical methods. The developed calculation scheme with two compaction zones around driven piles can provides reasonable estimates of vertical displacements of the soil base.

RÉSUMÉ: Le problème abordé dans cet article concerne l'utilisation de l'argilite comme base pour les fondations aux pieux battus. Lors de l'utilisation des fondations données dans les sols a lieu la formation des zones de compactage autour du pieu battu. L'objectif de la présente étude est d'analyser l'influence des zones de compactage sur les résultats des calculs numériques pour les prévisions de l'affaissement du pieu battu sur les argilites. Cette étude a permis de résoudre les problèmes suivants: 1) On a analysé les recherches effectuées dans le domaime des affaissements des pieux dans les sols argileux; 2) On a décrit les conditions des terrains experimentaux ainsi que la méthode des essais des pieux battus sur les argilites; 3). On a calculé l'affaissement du pieu solitaire par les méthodes numériques suivant la programmation Plaxis 3D; 4) On a comparé les données experimentales avec les résultats des calculs par les méthodes numériques. Notre schéma théorique à deux zones de compactage autour du pieu battu assure l'évaluation adequate des déplacements de la fondation du sol.

Keywords: Driven pile; Plaxis; Claystone; Settlement; Numerical method

1 INTRODUCTION, PURPOSE AND TASKS

The development of urban infrastructure, social, transport, environmental and economic problems are typical for modern cities. This leads to the need for underground space and deep pile foundation development. Pile foundations can consist of non-displacement and displacement (driven) piles in accordance with an installation method. Driven pile foundations are widely used due to their simple installation and efficiency. The installation of displacement pile involves driving or jacking process that causes changes in soil condition and stress-strain state affecting the pile settlement and the bearing capacity (Meyerhof 1976, Randolph et al. 1979). Changes in soil condition around the driven pile increase soil density and horizontal stress around pile shaft. Bartolomey et al. (2001) carried out field tests on six experimental sites and proved that a compaction zones with altered values of the physical and mechanical soil properties were formed along the side and under the tip of the pile as a result of pile driving. To determine the properties of clays in the compaction zone, boreholes were drilled and the piles were dug up. Clay samples were taken and studied in the laboratory. Cone penetration tests were carried out around the driven piles. Bartolomey et al. (2001) presented the values of the mechanical and physical properties of clays and loams in the zones affected by pile driving. The compaction zones in the horizontal direction were of 6 - 7 *d* for single piles and 10 - 11 *d* for strip pile foundations (here and elsewhere, *d* is the length of pile side). The compaction zone in the plane of the tip of a single pile was formed to a depth of 3 to 3.5 *d* and 4 to 5 *d* for strip pile foundations. In the compaction zone bordering the pile the specific weight of the clay increased by 12 %, and the modulus of clay deformation increased by 283 % as compared to the natural soil. The degree of change in clay properties decreased with distance from the driven pile.

Large areas of Russia (Ponomaryov and Sychkina 2015), Europe (Bond and Jardine 1991, Cooke et al. 1989, Zhang et al. 2010), China (Suxin et al. 2006) and of many other countries of the world are characterized by the spread of ancient hard clay. These deposits can be represented by claystones and their varieties weathered to clays, loams and crushed stones. The weathered ancient hard clays mentioned above are used as bases for pile foundations. Numerical modeling by the methods of nonlinear analysis is widely used to describe the behavior of single pile and pile groups in layered clays (Fattah. et al. 2012, Sheil and McCabe 2016, Huang et al. 2011, Ai and Cheng 2013). The majority of numerical solutions are based on the field pile-load tests results. However, the compaction zones in the soils around the pile were not taken into account in calculation. Thus, it can be assumed that taking into account the compaction zones will increase the accuracy of calculations and the correction of numerical solutions that were carried out with the help of software systems will not be needed.

The purpose of this study is to recommend the use of compaction zones when calculating the prediction of driven pile settlement on claystones. The following tasks were solved:

1) the analysis of the data obtained from full-scale field testing of statically loaded pile on the experimental site in the city of Perm (Russia) was carried out;
2) the settlement of a single pile by numerical methods in Plaxis 3D without considering and with taking into account the formation of compaction zones in the soils and claystones around the pile was determined;
3) the results of calculations by numerical methods and field pile tests were compared;
4) recommendations on the applicability of compaction zones in numerical methods for predicting the settlement of a single pile in layered soils and claystones are given.

2 RESEARCH METHODOLOGY

2.1 General information

The investigation of the vertical settlement of a driven pile on a layered soil base was carried out. The layered soil base consisted of

Quaternary clays and Early Permian claystones. Numerical calculation with the help of the Plaxis 3D program complex was carried out using two schemes, without taking into account compaction zones around the driven pile and with those. The amount of pile settlement obtained by numerical modelling were compared with those obtained during field tests.

2.2 *Experimental site and full-scale pile testing*

The experimental site is located in the city of Perm (Russia) and has complex geological conditions. Early Permian claystones overlain by Quaternary clay deposits are involved in geological structure of the experimental site. Underground waters were observed at a depth from 16.4 to 23.3 m and were below of the pile tip. Full-scale tests of statically loaded piles № 407, 592, 403, 587 were carried out on the experimental site. The piles under test were reinforced concrete driven piles with cross section of 0.3 x 0.3 m. The length of pile № 407 was 8.0 m, the length of piles № 592, 403 was 10.0 m, and the length of pile № 587 was 5.0 m. The ground under the tip of the pile was represented by claystone. All piles penetrated into the claystone to a depth of no less than 1 m. The maximum load on the piles was 1.1 MN (Pile №407) and 1.2 MN (Piles № 592, 403, 587). The load on the pile was carried out in steps of 100 kN and 200 kN.

2.3 *Numerical modelling*

The physical and mechanical parameters of soils and claystones were determined from triaxial and oedometer tests. Results of laboratory tests were adjusted in the SoilTest (Plaxis 3D). The initial data of the geological conditions of full-scale tests of pile № 407, 592, 403, 587 were used for modeling “ground base – pile foundation” system.

Numerical calculations were performed using the commercial PLAXIS 3D software. The Hardening Soil model was applied for all Quaternary soils. The Hardening Soil and Linear-Elastic numerical models were used for claystone A linear-elastic model was used to model the pile material. Piles were loaded stepwise in numerical modeling. The step value of the load stage was similar to that in the field pile tests. Numerical calculations were carried out by two schemes:

1) without considering the compaction zone in the clay and claystones around the driven pile;
2) taking into account compaction zone in the clay and claystones around the driven pile according to Bartolomey et al. (2001).

The following soil compaction zones in the space around the driven pile according to Bartolomey et al. (2001) are marked:

1) The first zone is located in the space near the pile with a radius equal to 3d (d is the length of a pile side). It has the specific soil gravity increased by 12 % and the soil deformation modulus increased by 283 % as compared to the natural soil.

2) The second zone is located in a space near the pile with a radius from 3d to 7d (d is- the length of a pile side). It has the specific soil gravity increased by 7 % as compared to the natural soil.

3) The third zone does not have a clear boundary and does not influence the bearing capacity and the pile foundation settlement. The values of the parameters for this zone were assumed equal to the natural soil.

3 RESULTS OF INVESTIGATION

The values of field pile settlement for piles № 407, 592, 403, 587 varied within the limits of 2.17 - 3.37 mm and are shown in Fig. 1 - Fig.4.

It is seen that the settlement of field piles is almost linear. It is, probably, due to the stiffness of the claystone, which is under the lower tip of all four piles.

As you can see from Figures 1-.4, numerical calculation without compacted zones around the pile showed high values of pile settlements. The difference between the calculated and field results was in the range of 2.7 - 21.5 times. Thus, overrunning of the results of pile settlement calculation as compared with the field tests was significant taking no account of the compaction zones.

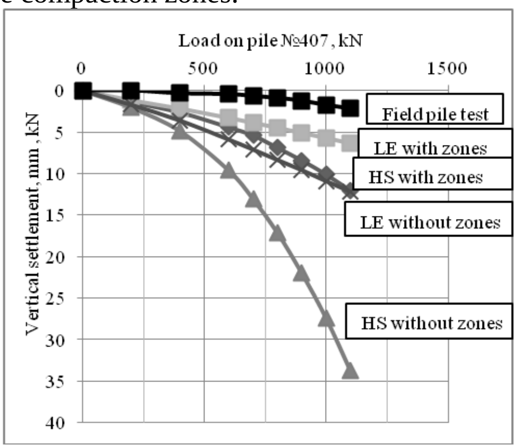

Figure 1. Graphs of settlement for pile № 407, here: LE – linear-elastic model, HS - Hardening Soil model

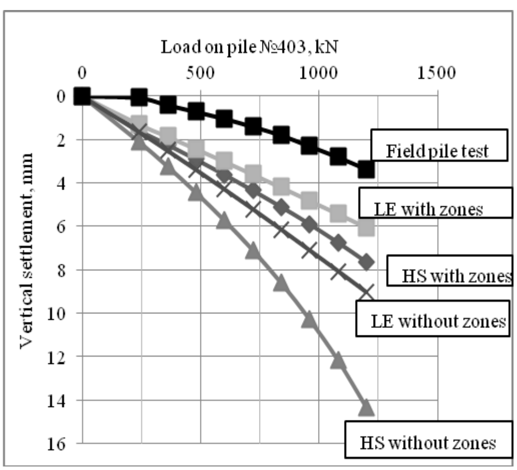

Figure 2. Graphs of settlement for pile № 403, here: LE – linear-elastic model, HS - Hardening Soil model

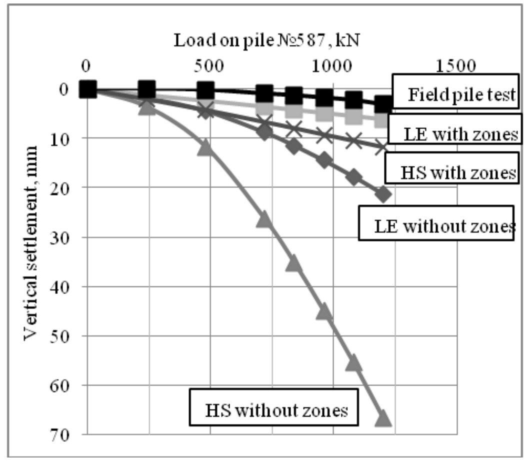

Figure 3. Graphs of settlement for pile № 587, here: LE – linear-elastic model, HS - Hardening Soil model

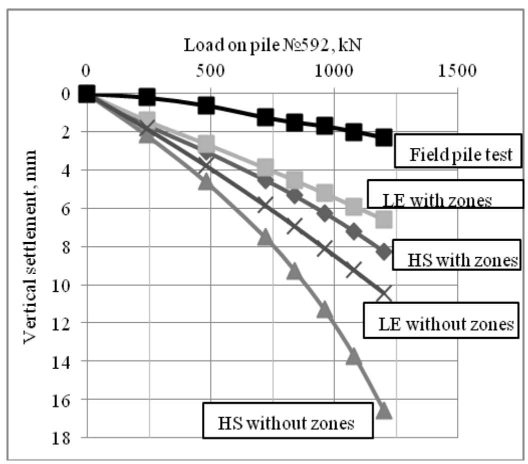

Figure 4. Graphs of settlement for pile № 592, here: LE – linear-elastic model, HS - Hardening Soil model

Pile settlement graphs obtained by numerical methods based on compaction zones around piles are shown in Figures 1 - 4. Calculation with the use of the Hardening Soil model with due regard of compaction areas around the driven pile in showed the values close to those obtained under field pile test. The difference between the numerical calculations with the use of the Hardening Soil model and the results of field tests was in the range of 2.3 – 6.9 times.

Numerical calculation with the use of the Linear-Elastic model for claystone and the Hardening Soil model for Quaternary soils taking into account the compaction zones around the pile, showed good convergence with the field tests of piles. The difference between the numerical calculations and the results of field tests was in the range of 1.8 – 2.9 times. These results clearly demonstrate that the calculation of driven pile settlement with compacted zones is close to the field pile investigation. Soil compaction around the driven pile increases end bearing and skin friction of pile. The influence of compacted zones in soils around the driven pile has been investigated to optimize the design of pile foundations. Based on the results of the research, the authors recommend using the Hardening Soil model for Quaternary soils and Linear-Elastic model for Permian claystone with taking into account the compaction zones around the driven pile. This method shows the exact values of settlement with no correction of the existing numerical calculation models.

In the study we attempted to analyze the compaction zones in the soils and claystones space around the driven pile that influence on the pile settlement. The obtained results are in good agreement with the previously performed investigations of driven pile behavior in layered clays (Bond and Jardine 1991, Meyerhof 1976, Randolph et al. 1979, Zhao et al. 2013). It confirms that the installation of displacement pile involves driving process that causes changes in soil properties and stress-strain state. However, changes the values of clay parameters were not taken into account in the previously performed investigations. The authors believe that the application of this design scheme and values of clay parameters is a simple and effective way to improve the accuracy of calculation of the driven pile settlement.

We can speak about the practical application of the calculations carried out by numerical methods implemented in the software package PLAXIS 3D with due regard for the compaction zones in the calculation scheme for the settlement of piles driven into claystones. For claystone we can recommend the use of the Linear-Elastic model. For Quaternary clays, we can recommend the use of the Hardening Soil model, which also showed good results taking into account the compaction zones in the calculation scheme. Case study indicates the calculation procedure can also help to understand the behavior of driven pile in layered clays. It may be stated that the experimental data prove the role of compaction zones in the clay and claystone in the process of vertical displacements of driven pile. In this way, it can be assumed that the inclusion of compaction zones will increase the accuracy of calculations without correction of numerical solutions implemented in software complexes.

4 CONCLUSIONS

The results obtained are important for predicting the settlement of a driven pile in layered soils and claystones. Clay compaction around the driven pile increases end bearing and skin friction of pile. The developed calculation scheme with compaction zones can provides reasonable estimates of vertical displacements of the clay base. The application of this calculation scheme is a simple and effective way to improve the accuracy of calculation of the driven pile settlement in layered soils and claystones.

It was investigated that the calculation of the driven pile settlement with no account taken of the compaction zones around the pile gives higher settlement values than those for the piles used in the field tests. The difference between the calculated results without considering the compaction zone around the driven pile and field pile tests was in the range of 2.7 - 21.5 times.

The calculation with taking into account the compaction zones around the driven pile showed the settlement values close to those obtained during the field tests of the piles. In this case, the difference between the numerical calculations and the results of field tests was in the range of 1.8 – 6.9 times. For Quaternary clays, we can recommend the use of the Hardening Soil model, which showed good results taking into account the compaction zones in the calculation scheme. For Permian claystones, we can recommend the use of the Linear-Elastic model.

Calculation with due regard for the compaction zones around the driven pile shows the exact values of the pile settlement with no correction of the existing numerical methods. Represented conclusions are true for one experimental site with layered clays and claystones and should be verified and evaluated in other experimental sites.

5 ACKNOWLEDGEMENTS

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