Effect of clay compaction around driven pile and prediction of pile settlement

Andrey Ponomaryov[1,2*] and *Evgenia* Sychkina[1]

[1]Perm National Research Polytechnic University, 29, Komsomolsky Avenue, Perm, 614990, Russia
[2]St. Petreburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

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

1 Introduction

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. According Meyerhof 1925, Randolph et al.1979 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. 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

* Corresponding author: andreypab@mail.ru

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.

According to De Beer 1988, Azzouz and Morrison 1988, geotechnical design is often based on empirical correlations, including some modification factors for predicting pile behavior, such as a soil type, soil anisotropy, "pile-ground" and "pile -ground-pile" interactions. Pile settlement and bearing capacity in clays depend on the bearing capacity in the tip and the lateral friction. The settlement of single driven pile in soft clay is described by analytical and numerical solutions and is directly related to the dissipation of excess pore water pressure caused by pile driving [1-3]. According to Lehane & Jardine 1994 when the pile rests on hard clay, it is assumed that the total load acts at the pile tip, i.e. it is an "end-bearing pile". Large areas of Russia [4, 5], Europe [6], 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. Thus, one of the current problems of active underground space development is the prediction of driven pile behavior rested on the layered clay and claystone's bases. Numerical modeling by the methods of nonlinear analysis is widely used to describe the behavior of single pile and pile groups in layered clays [7-10]. The majority of numerical solutions are based on the field pile-load tests results. However, the compaction zones in the clays around the pile were not considered in calculation. Thus, it can be assumed that considering 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 in layered clay soils. 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 2D without considering and with considering the formation of compaction zones in the clay around the pile was determined;

3) the settlement of a single pile by the analytical method without considering and with considering the formation of compaction zones in the clay around the pile was determined;

4) the results of calculations by numerical and analytical methods with those of field pile tests were compared;

5) recommendations on the applicability of compaction zones in numerical and analytical methods for predicting the settlement of a single pile in layered clays and claystones are given.

The authors believe that the proposed recommendations for determining the settlement of a single pile in layered clay and claystone can be used for similar geological conditions. Recommendations and calculations are presented for examination and verification in other geological conditions and for a group of driven piles.

2 Materials and methods

2.1 General information

The investigation of the vertical settlement of a driven pile on a layered clay base was carried out. The layered clay base consisted of Quaternary clays and Early Permian claystones. Much attention was paid to the compaction zones in the clay and claystone space around the driven pile. Numerical calculation with the help of the Plaxis 2D program complex was carried out for different soil models using two schemes, without considering compaction zones around the driven pile and with those. The amount of pile settlement obtained by numerical modelling and analytical calculations were compared with those obtained during field tests.

2.2 Description of experimental site and methodology of full-scale pile testing

The experimental site is located in the city of Perm (Russia) and has complex geological conditions (Figure 1). As it can be seen in Figure 1, clay dominates in geological cross-section. Early Permian claystones (P_1) overlain by Quaternary clay deposits (Q_{IV}) 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.

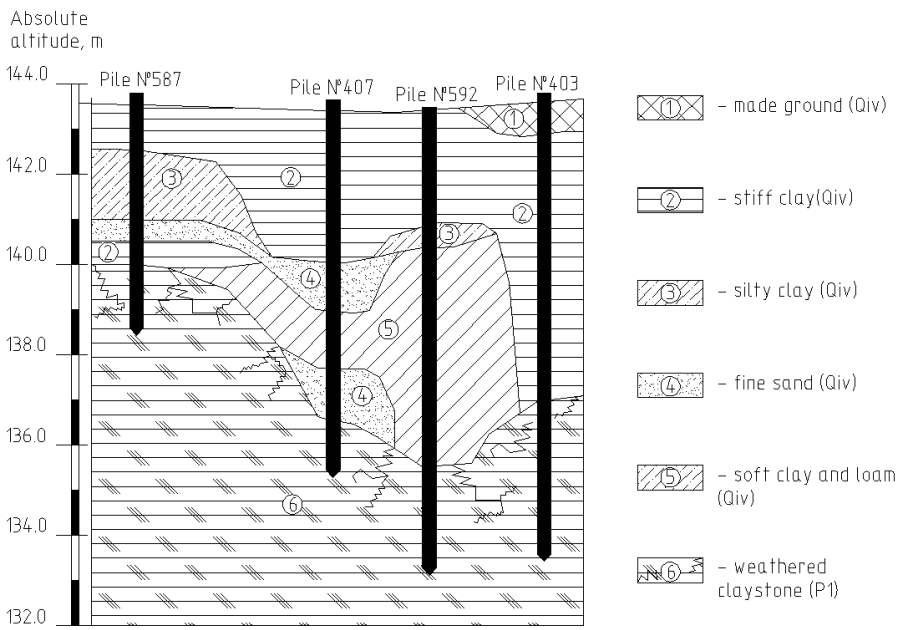

Fig. 1. Geological conditions of the experimental site.

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 pile material was concrete with an elastic modulus of 30000 kN/m^2. 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 modeling of pile settlement and stress-strain state of clay and claystone under pile load

Numerical calculations were performed using the commercial PLAXIS 2D software [11]. The problem was solved as axial-symmetric. The *finite element* model, which represented half of the cross-section, was assumed to be 5.0 m wide and 15.0 m high. Such dimensions were chosen to solve the problem for the layered clay model and estimate the range of the stress-strain response. The initial conditions were applied for the effective natural stress. Boundary conditions were as follows: the vertical displacement was limited by the bottom of the model, the horizontal displacement by the far vertical edge. Gravitational force was applied to the whole numerical model. The amplitude of the load was applied to the upper end of the analyzed piles. This load was the same as the loading steps in the field test of piles under load.

Numerical calculations were carried out by two schemes:

1) without considering the compaction zone in the clay and claystones around the driven pile;

2) considering 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.

The physical and mechanical parameters of clay and claystone were determined in accordance with Russian standards and guidelines for PLAXIS 2D [11]. The values of natural clay parameters and those calculated according to Bartolomey et al.2001.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. The Mohr-Coulomb model was applied for all Quaternary clays on the experimental site. The Mohr-Coulomb, Jointed Rock and Hardening Soil numerical models were used for claystone. A linear elastic model was used to model the pile material. The following parameters were used to model a pile: the modulus of concrete elasticity of 30000 kN/m^2, the specific gravity of 23.5 kN/m^2, the Poisson's ratio of 0.2. Piles were loaded stepwise in numerical modeling. The step value of the load stage was similar to that in the field pile tests.

2.4 Analytical calculation of pile settlement

The analytical settlement calculation of piles № 407, 592, 403, 587 was carried out in accordance with the method described in Russian standard SP 24.13330.2011:

$$S = \beta \frac{N}{G_1 l}, \quad (1)$$

where N = vertical load on the pile, MN;
G_1 = shear modulus for Quaternary clays;
G_2 = shear modulus of the soils below the tip of the pile (claystones);
l = length of the pile, m;
β = coefficient determined by the formula:

$$\beta = \frac{\beta\prime}{\lambda_1} + \frac{1-(\beta\prime/\alpha\prime)}{\chi}, \quad (2)$$

where $\beta' = 0{,}17\ln(k_v G_1 l/G_2 d)$ = coefficient of an absolutely rigid pile;
$\alpha' = 0.17\ln(k_{v1} l/d)$= coefficient for the ground base with characteristics G_1 and ν_1;
d = cross-sectional pile diameter;
$\chi = EA/G_1 l^2$= relative stiffness of the pile;
EA = stiffness of the pile shaft under compression, MN;
A = cross-sectional area of the pile, m^2;
E = the elasticity modulus of the pile material;
λ_1 = parameter for determining the settlement after the pile shaft compression: $\lambda_1 = \frac{2.12\chi^{3/4}}{1+2.12\chi^{3/4}}$;
k_v, k_{v1} = coefficient determined by the formula:

$$k_v = 2.82 - 3.78v + 2.18v^2, \quad (3)$$

where $v = (v_1 + v_2)/2$ and $v = v_1$;
v_1 = Poisson's ratio for Quaternary clays;
v_2 =Poisson's ratio for soils under pile tip (claystones).

According to this method, the soil under the pile tip is accepted as linearly deformed half-space. The analytical calculation is also carried out for two cases: without compaction zones around the driven pile and their considering with improved clay parameters.

3 Results

3.1 Results of analytical and numerical calculations without compaction zones in clays around piles

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 Figure 2 – Figure 5. It is seen that the settlement of field piles is almost linear. It is, probably, due to the stiffness of the argillite, which is under the lower tip of all four piles.

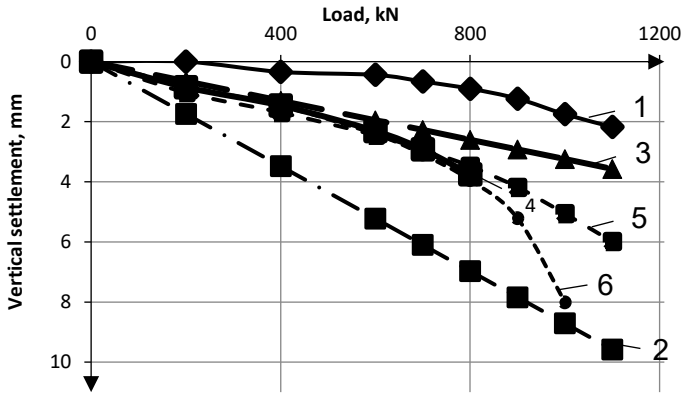

Fig. 2. Graphs of settlement for pile № 407, here: 1 is the field pile-load test; 2, 3 is analytical method SP 24.13330.2011 with no account taken of the compaction zones and with due regard for them, respectively; 4, 5, 6 is the numerical method with compaction zones for Mohr-Coulomb model, Hardening Soil model and Jointed Rock model, respectively.

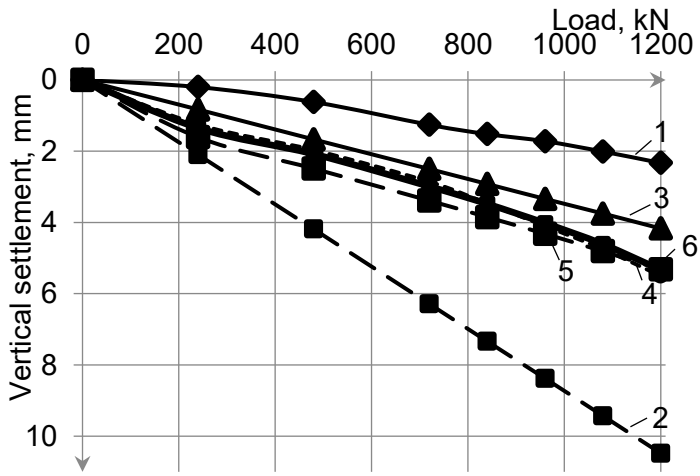

Fig. 3. Graphs of settlement for pile № 592, here: 1 is the field pile-load test; 2, 3 is analytical method SP 24.13330.2011 with no account taken of the compaction zones and with due regard for them, respectively; 4, 5, 6 is the numerical method with compaction zones for Mohr-Coulomb model, Hardening Soil model and Jointed Rock model, respectively.

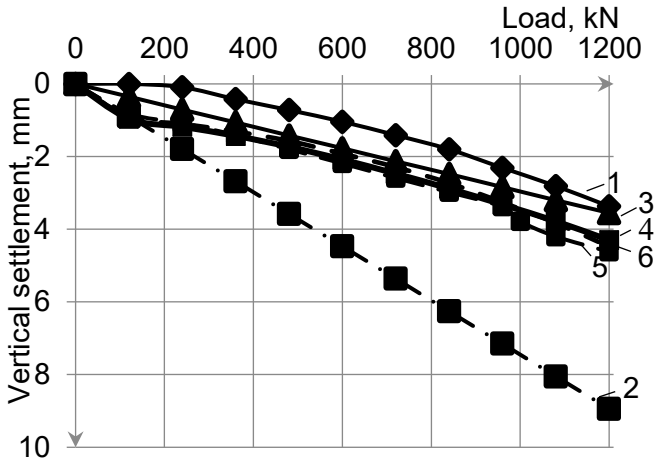

Fig. 4. Graphs of settlement for pile № 403, here: 1 is the field pile-load test; 2, 3 is analytical method SP 24.13330.2011 with no account taken of the compaction zones and with due regard for them, respectively; 4, 5, 6 is the numerical method with compaction zones for Mohr-Coulomb model, Hardening Soil model and Jointed Rock model, respectively.

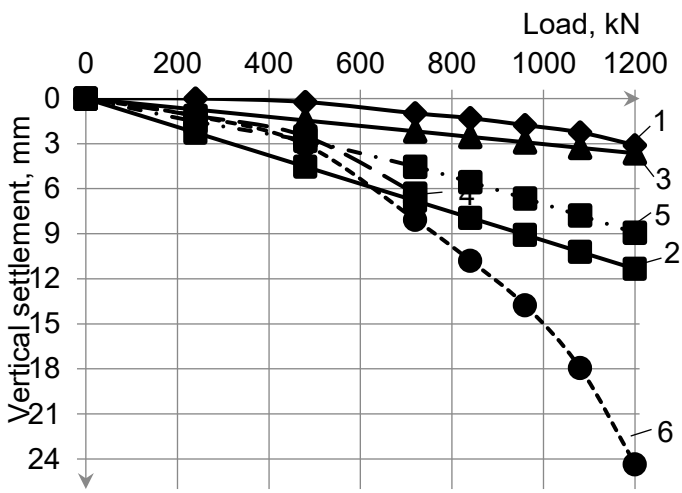

Fig. 5. Graphs of settlement for pile № 587, here: 1 is the field pile-load test; 2, 3 is analytical method SP 24.13330.2011 with no account taken of the compaction zones and with due regard for them, respectively; 4, 5, 6 is the numerical method with compaction zones for Mohr-Coulomb model, Hardening Soil model and Jointed Rock model, respectively.

As you can see from Figure 2- Figure5, numerical calculation with the use of the Mohr-Coulomb, Jointed Rock and Hardening Soil models, realized in Plaxis 2D without compacted zones around the pile, showed high values of pile settlements. Their difference from those of field tests for all piles was in the range of from 2.6 to 18.8 times for Jointed Rock model, in the range of 2.4 to 8.6 times for Hardening Soil model with the load on the pile equal to 1.1 MN. For short piles № 407 and 587 the calculation with the use of the Mohr-Coulomb model was carried out for the maximum load of 0.8 MN. After that, the bearing capacity of piles № 407 and 587 for the Mohr-Coulomb model was depleted and

clays had plastic deformations. The difference between the calculated and field results was in the range of 2.3 - 4.0 times for the Mohr-Coulomb model.

Analytical calculation excluding compaction zones around the piles also showed high values of pile settlement. For example, the analytical calculation of the pile settlement exceeded the settlement of the field pile in the range of 2.9 - 4.7 times for the load on the pile of 1.1 MN. The graphs of the pile calculations obtained by the analytical method without considering the compaction zones are also shown in Figure 2 – Figure 5 for comparison.

Thus, overrunning of the results of pile settlement calculation as compared with those of the field tests was significant taking no account of the compaction zones. This calculation scheme does not reflect the real interaction of clay base and driven pile. This statement is true both for numerical and analytical calculations. The use of a design scheme without compaction zones in clays does not allow obtaining exact values of the driven pile settlement.

3.2 Results of analytical and numerical calculations with compaction zones in clays around piles

Calculation with due regard of compaction areas around the driven pile in showed the values close to those obtained under field pile test. This observation is true both numerical and analytical methods calculation. Pile settlement graphs obtained by numerical and analytical methods based on compaction zones around piles are shown in Figure 2 – Figure 5.

As it is seen in Figure 2 – Figure 5 analytical calculations with compaction zones in clays around the pile are in good agreement with those of field pile tests. For example, the analytical settlement calculation exceeds the settlement of the field piles in the range of 1.1 - 1.9 times for the load on the pile of 1.1 MN. Numerical calculation with the use of the Mohr-Coulomb, Jointed Rock and Hardening Soil models considering the compaction zones around the pile, also showed good convergence with the field tests of piles. For long piles № 592 and № 403, the results of calculations with the Mohr-Coulomb, Jointed Rock and Hardening Soil models were close to each other and to the value of the full-scale pile settlement. The difference between the numerical calculations and the results of field tests was in the range of 1.3 - 2.4 times with the load on piles of 1.1 MN. For short piles № 407 and № 587 numerical calculations using the Hardening Soil model showed the closest results to the field pile tests. The difference between the numerical calculations and the results of field tests was in the range of 2.8 – 3.5 times for the load on the pile of 1.1 MN. For short piles № 407 and № 587, the calculation with the Mohr-Coulomb model was carried out for a maximum load of 0.7 - 0.8 MN. This again illustrates the importance of considering the compaction zones in the design scheme for predicting pile settlement in layered clay soils.

These results clearly demonstrate that the calculation of driven pile settlement with compacted zones is close to the field pile investigation. Clay compaction around the driven pile increases end bearing and skin friction of pile. This calculation scheme shows the real "clay base - driven pile" interaction. The influence of compacted zones in clays 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 analytical method SP 24.13330.2011 to predict the settlement of a single driven pile on layered clays and claystones with due regard for compaction zones. To predict the settlement of a single driven pile by numerical methods implemented in Plaxis 2D software, the authors recommend using the Hardening Soil model for claystone considering the compaction zones around the driven pile. For Quaternary clays, the authors recommend using the Mohr-Coulomb model, which also showed good results when considering the compaction zones in the calculation scheme.

Thus, considering the compaction zones around the driven pile shows the exact values of settlement with no correction of the existing calculation methods.

4 Discussion

In the study we attempted to analyze the compaction zones in the clay and claystone 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 [2, Bond & Jardine. 1991]. It confirms that the installation of displacement pile involves driving process that causes changes in clay properties and stress-strain state. However, changes the values of clay parameters were not considered 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 analytical method SP 24.13330.2011 and the numerical methods implemented in the software package PLAXIS 2D for the Hardening Soil model, with due regard for the compaction zones in the calculation scheme for the settlement of piles driven into claystones. For Quaternary clays, we can recommend the use of the Mohr-Coulomb model, which also showed good results considering 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.

5 Conclusion

In this paper, the compaction zones in layered clay soils around driven piles were numerically studied with the use of a two-dimensional finite element model. The bases composed of clays and claystone should be designed with due regard for their specific features, which are formed as a result of pile driving. Two compaction zones in clays and claystones around the driven pile should be considered for settlement calculation:

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.

The results obtained are important for predicting the settlement of a driven pile in layered clay soils. 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. This calculation scheme shows the real “clay base - driven pile” interaction. 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 clay soils. 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. Overrunning of calculation results of the driven pile settlement in comparison with those obtained under field test was significant with no account taken of compaction zones in clays. This statement is true both

for the numerical calculation and for analytical calculations. For the analytical calculation the difference varied from 2.9 to 4.7 times; for the numerical calculation from 2.3 to 18.8 times.

The calculation with considering 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, for the analytical method, the difference was in the range of 1.1-1.9 times and 1.3-3.5 times for the numerical calculation when using the Hardening Soil model. We can speak about the practical application of the calculations carried out by analytical method SP 24.13330.2011 and the numerical methods implemented in the software package PLAXIS 2D for the Hardening Soil model, with due regard for the compaction zones in the calculation scheme for the settlement of piles driven into claystones. For Quaternary clays, we can recommend the use of the Mohr-Coulomb model, which also showed good results considering the compaction zones in the calculation scheme.

Based on the results of the research, the authors recommend using analytical and numerical methods, considering the compaction zones to predict the settlement of a single pile in layered clay soils. 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 calculation methods. Represented conclusions are true for one experimental site with layered clays and claystones and should be verified and evaluated in other experimental sites.

References

1. S. Bensallam, L. Bahi, H. Ejjaaouani, et al., Soils and Foundations **54**, 109-115 (2014). DOI: 10.1016/j.sandf.2014.02.003
2. C. Y. Zhao, W. M. Leng, G. Y. Zheng, Appl. Clay Sci. **79**, 8–12 (2013). DOI: 10.1016/j.clay.2013.02.022
3. K. Gavin, D. Gallagher, P. Doherty, B. McCabe, Canadian Geotechnical Journal, **47 (7)**, 730-741 (2010). DOI: 10.1139/T09-146
4. A. B. Ponomaryov and E. N. Sychkina, Appl. Clay Sci. **114**, 61-169 (2015). DOI: 10.1016/j.clay.2015.05.023
5. S. V. Kuznetsova, S. I. Makhova, Procedia Engineering **150**, 2218- 2222 (2016). DOI: 10.1016/j.proeng.2016.07.267
6. C. L. Zhang, K. Wieczorek, M. L. Xie, Journal of Rock Mechanics and Geotechnical Engineering **2(1)**, 44-51 (2010). DOI: 10.3724/SP.J.1235.2010.00044
7. M. Y. Fattah, K. T. Shlash, S. M. Al-Soud Madhat, Journal of Rock Mechanics and Geotechnical Engineering **4(1)**, 28-43 (2012). DOI: 10.3724/SP.J.1235.2012.00028
8. B. B. Sheil and B. A. McCabe, Computers and Geotechnics **75**, 145-158 (2016). DOI: 10.1016/j.compgeo.2016.02.001
9. M. Huang, F. Liang, J. Jiang, J., Computers and Geotechnics **38**, 875-882 (2011). DOI: 10.1016/j.compgeo.2011.06.002
10. Z. Y. Ai, Y. C. Cheng, Y.C., Engineering Analysis with Boundary Elements **37**, 327–335 (2013).DOI: 10.1016/j.compgeo.2019.103437
11. R. B. J. Brinkgreve, W. Broere, D. Waterman, Plaxis 2D-version 9. Finite Element Code for Soil and Rock Analyses (User Manual. Rotterdam, Balkema, 2008)