

## Consideration of piling technology during interaction with the soil at their contact

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**ABSTRACT:** Most of the existing pile settlement calculation methods are based on the assumption that the settlement of the pile is equal to the settlement of the adjacent soil. However, numerous experimental studies have shown that, in reality, the mechanical properties of the soil change at the pile-soil contact and the pile can break off and slip when the ultimate strength of the soil is reached. In this paper, a graph-analytical method for calculating pile settlement is proposed, which makes it possible to take into account the non-linear behaviour of the soil over the entire surface of the pile, the possibility of its detachment and slippage after reaching the ultimate strength of the soil, changes in the properties of the contact zone soils and the mechanism of load distribution over the pile. The main purpose of this paper is to investigate the influence of the friction coefficient (strength reduction factor  $R_{inter}$ ) on the results of settlement calculations and to determine the scope of application of the graph-analytical solution depending on the piling technology. A comparative analysis of the calculation results was performed with the numerical method in the geotechnical software package Plaxis, as well as with the results of field tests of piles by static loading. The tests of driven pile and bored pile were used for verification. Based on the results of the comparative analysis of the results of calculations and static pile tests, the graphs of settlement-load dependence were plotted, conclusions were drawn about the influence of friction coefficients on the results of the pile settlement calculation and recommendations were given on the application of the graph-analytical solution depending on the technology of pile construction.

**KEYWORDS:** Pile-soil interaction, friction coefficient, installation effect, graph-analytical solution, pile settlement.

### 1 INTRODUCTION

It is well known that at the contact of structures with the soil there is a change in mechanical characteristics depending on various factors, which can be accounted for by such a parameter as the interface friction coefficient (strength reduction factor  $R_{inter}$ ). When designing, the consideration of this coefficient and its value have a significant impact on the forces in the structures and their displacements. The greatest influence on the properties of the contact zone, i.e. the value of the interface friction coefficient, which is characterized by the change in the properties of the contact zone, is exerted by the technology of constructing structures in the soil. In this case, mechanical characteristics at the contact can both decrease and increase. For example, in the work of the authors, based on the results of experimental studies of pile performance under load, it was noted that the shear resistance at the contact was higher when bored piles were placed under the protection of bentonite mortar and was lower when piles were placed under the protection of casing. In another work, the change of mechanical characteristics at the contact of bored-injection pile with soil was investigated. As a result of a 10% increase in the density of the soil near the pile space, the deformation characteristics of the soils at the contact with the pile increased by 17.4%, and the strength characteristics increased by 27.3%.

In addition to the pile-in-soil technology, the change in mechanical properties is also affected by the type of soil and the pile material, as contact friction is characterized by the meshing of soil particles with the roughness of the construction material. Therefore, the rougher the particles and rougher the surface of the construction material, the higher the friction will be and vice versa. One of the first papers to evaluate the effect of various factors on friction in the contact zone is Potyondy J.G. 1961. It described direct shear tests on cubic shaped specimens, which were carried out on steel and concrete of different roughness and wood. The lowest values of friction coefficient were obtained for smooth steel - 0.44, the highest values, close to 1, for rough concrete and wood. In the work of Isaev O.N. and Sharafutdinov R.F. studied the strength reduction factor at the contact of sandy and clayey soils with different materials: for steel the friction coefficient varies from 0.371 to 1.0, for

concrete - from 0.603 to 1.0, for polymer - from 0.402 to 1.0. At the same time, the obtained values significantly exceed the recommended normative values. In the authors' work, the interface friction coefficient was determined at the contact of clay and sandy soils with polymers and steel in a direct shear device. The results of laboratory tests showed that the interface friction coefficient at the contact with steel turned out to be 0.64...0.80, and at the contact with polymer 0.80...0.94. Similar studies of changes in mechanical characteristics of soils with structural materials by laboratory methods depending on various factors have been investigated by other authors.

However, the interface friction coefficient  $R_{inter}$  can also be determined in another way: by inverse calculation using numerical simulation. Using the results of field tests of piles by static loading, such as graphs of settlement-load dependence or distribution of shear stresses along the lateral surface of the pile, such values of this coefficient are numerically selected so that the results of static tests converge with the numerical one. For example, in the work of V.A. Vasenin based on the results of reverse calculation, the strength reduction factor  $R_{inter}$  at the contact of soils and bored pile were: 0.7 - for loams, 1.0 - for sandy loam and sand, 0.4 and less - for clays. In another work, the authors, using the results of a field test of a steel pile, obtained the interface friction coefficient equal to 0.45 by reverse calculation in the Plaxis program complex. The analysis of their calculation results showed that the application of this coefficient allowed to obtain excellent qualitative and quantitative convergence of the shear stress distribution diagram over the depth of the pile and the graph of the load-dependent settlement. In the absence of taking this coefficient into account in numerical modeling, convergence with the results of field testing of the pile is not observed. In another paper, based on the results of field tests of long-length bored piles, the obtained values of the  $R_{inter}$  strength reduction factor lie in the range of 0.75...1.0.

### 2 MATERIALS AND METHODS

The settlement of a single pile interacting with a soil with elastic-plastic properties was calculated using the graph-analytical method. This method has been proposed by authors

Ter-Martirosyan Z.G., Sidorov V.V. and Strunin P.V., however, in this paper it was modified by taking into account a number of factors that allow for a more accurate description of pile behavior under load. These factors include: nonlinear soil behavior both on the side and at the tip of the pile, exhaustion of the soil bearing capacity in areas of the pile's lateral surface where the ultimate soil strength has been reached, redistribution of loads along the pile, and reduced friction at the pile-soil interface. A more detailed description of this technique is given in papers [Ter-Martirosyan A.Z., Sidorov V.V., Almakaeva A.S.].

The graph-analytical method consists of two parts: analytical and graphical. In the analytical part of the method, a system of several equations is solved, which allow to determine the unknown components of the stress strain state of the soil mass: the reactive stress  $\sigma_0$  under the pile tip and shear stresses  $\tau_0, \tau_1, \tau_2, \tau_3, \tau_4$  and  $\tau_5$  along the lateral surface of the pile. To determine the unknown stress strain state components, a system of equations is prepared. Figure 1 shows the calculation diagram of the problem, indicating the forces acting on the pile and indicating the resulting stresses from the applied load  $N$ .

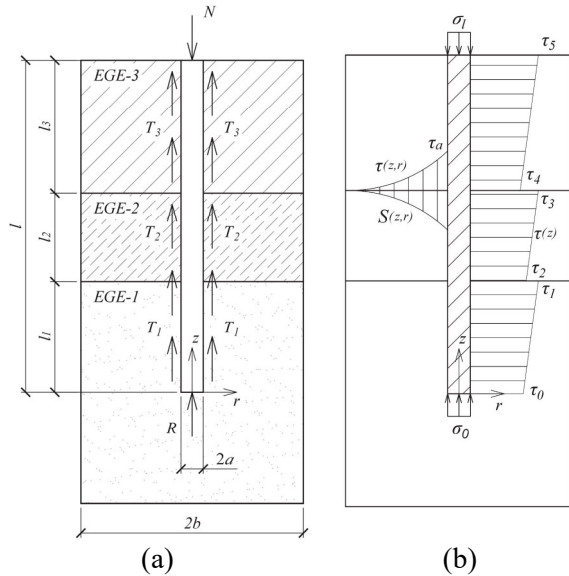


Figure 1. Calculation diagram of the analytical problem: (a) – indicating the acting forces, (b) – and the acting stresses.

The settlement of a single pile in a three-layered soil mass, taking into account the linear properties of the soils, will be determined as the sum of the settlement of the soil under the pile tip, the settlement due to compression of the pile shaft and the settlement of the soil on the lateral surface  $S_{lat}$  of the pile according to the formula:

$$S_{el} = S_{lat1} + S_{lat2} + S_{lat3} + \frac{\sigma_0 \cdot l \cdot \beta_{pile}}{E_{pile}} + \frac{\sigma_0 \cdot \pi \cdot a \cdot (1 - \nu_{soil1}) \cdot K}{4G_{soil1}} \quad (1)$$

where  $\beta_{pile}$  – coefficient of impossibility of lateral expansion of the pile material;

$E_{pile}$  – modulus of elasticity of the pile;

$l$  – pile length;

$a$  – pile radius;

$\nu_{soil1}$  – Poisson's ratio of the soil under the pile tip;

$G_{soil1}$  – shear modulus of the soil under the pile tip;

$K$  – coefficient depending on the depth of the die load.

Nonlinear settlement of the soil under the pile tip is determined by the formula:

$$S_{pl} = \frac{\sigma_0 \cdot \pi \cdot a \cdot (1 - \nu_{soil1}) \cdot K}{4G_{soil1}} \cdot \frac{p_{cr}}{p_{cr} - N} \quad (2)$$

where  $p_{cr}$  is the ultimate (critical) load determined by the Brinch Hansen formula.

To take into account the nonlinear settlement of the soil along the lateral surface of the pile, the graphical part of the method is used, in which the mobilized shear stresses are plotted according to the results of the analytical solution of the system of equations (Figure 2a) and the ultimate shear stresses are plotted according to the Coulomb-Mohr strength criterion (Figure 2b). By superimposing the epiphyses on each other (Figure 3), the areas where the bearing capacity has been exhausted and where there is still a safety margin for further redistribution of the load applied to the pile are determined.

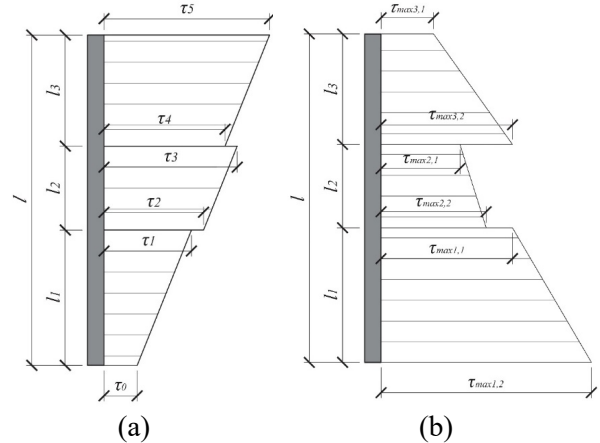


Figure 2. Typical diagrams: (a) – mobilized shear stresses, (b) – ultimate shear stresses.

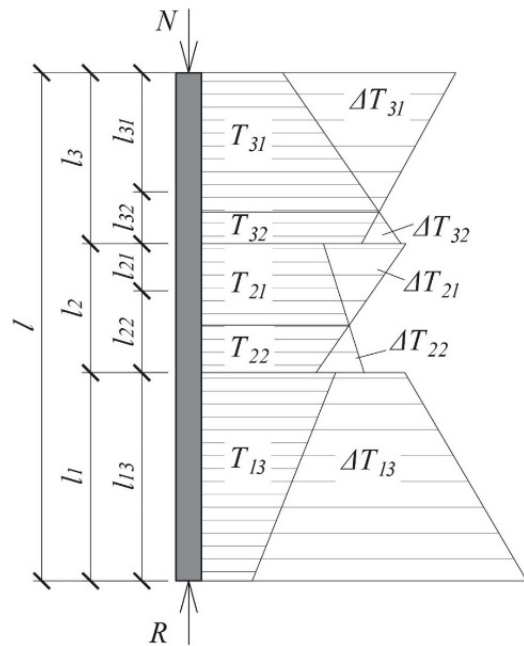


Figure 3. Epiphyses addition.

Verification of the graphical-analytical calculation method was performed with the results of numerical modeling in the Plaxis program and with the results of static tests of piles. In the first case, a bored pile 20 m long and 1.2 m in diameter was used, driven into soils whose properties are presented in Table 1.

Table 1. Physical and mechanical properties of soils (bored pile).

№ EGE	Soil type	$\gamma_{II}$ (kN/m <sup>3</sup> )	$\phi_{II}$ (°)	$c_{II}$ (kPa)	$E$ (MPa)
4	Loam	19.9	20	7	9.0
14	Sand	20.3	31	4	30.0
16	Loam	19.9	20	29	60.0

In the second case, a driven pile 6.7 m long and 35x35 cm in cross-section was driven into the soil by driving. The soil properties are presented in Table 2.

Table 2. Physical and mechanical properties of soils (driven pile).

No	EGE Soil type	$\gamma_{II}$ (kN/m <sup>3</sup> )	$\phi_{II}$ (°)	cII (kPa)	E (MPa)
1	Loam	20.4	27	35	19.0
2	Sand	19.9	34	6	22.0

### 3 RESULTS AND DISCUSSIONS

Based on the results of static tests of bored piles, as well as numerical and graphical-analytical calculations, the settlement-load curves shown in Figure 4 were constructed.

Verifying the graphical-analytical method against the results of static tests of a bored pile 20 m long and 1.2 m in diameter yielded satisfactory agreement between the settlement-load curves. A similar result was obtained using numerical modeling; however, the agreement between the graphical-analytical method and static tests was higher than that between the numerical method and static tests. This is due to the different nature of deformation: numerical calculations result in a more rapid accumulation of plastic deformations and a transition to nonlinear deformation.

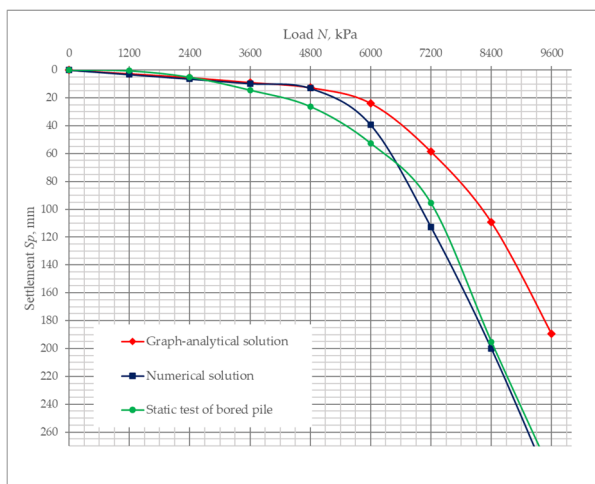


Figure 4. Graphs of settlement versus load of a bored pile without using the interface friction coefficients.

To take into account the change in friction at the "pile-soil" contact, characterized by the technology of pile installation, type of soil, pile material, etc., the interface friction coefficients (reduction in strength  $R_{inter}$ ) are used. The most accurate method for determining the interface friction coefficient is based on the selection of these coefficients by reverse calculation based on the results of known static tests of piles from a specific construction site. By reverse calculation, such values of this coefficient are selected so that the graphs of the dependence of settlement on the load coincide with the results of field tests of the pile. This method takes into account the pile material and soil type, but most importantly, it takes into account the pile installation technology. Generally, a value of this coefficient less than zero corresponds to bored piles, while a value greater than zero corresponds to piles driven without excavation. The  $R_{inter}$  coefficient was used only along the pile lateral surface, where friction occurs at the contact with the soil.

To improve the accuracy of the graphoanalytical and numerical calculations, the following  $R_{inter}$  interface friction coefficients were used in the calculations: 1.0 for sand and 0.9 for loam. The results, presented in Figure 5, demonstrate that using these coefficients improved the convergence of the graph-analytical curve with the static test of the bored pile. However,

the numerical method yielded worse results: using these coefficients resulted in even greater accumulation of plastic deformations, leading to pile failure. Therefore,  $R_{inter}$  interface friction coefficients should be used with caution in numerical modeling.

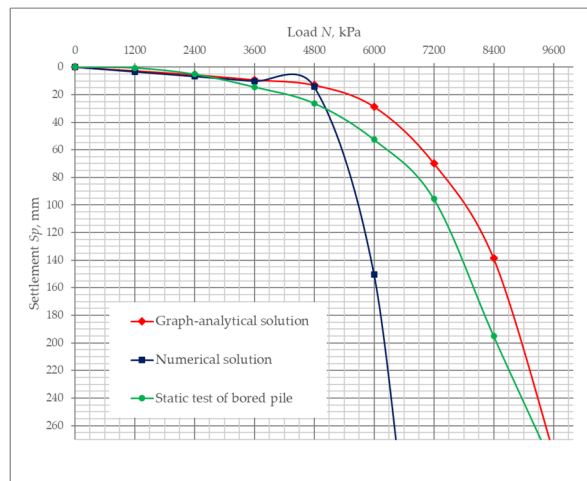


Figure 5. Graphs of settlement versus load of a bored pile with using the interface friction coefficients.

A similar situation is observed when verifying the results of the static test of a driven pile with the results of the graph-analytical calculation (Figure 6). However, due to the fact that the driven pile is driven without excavating the soil, the soil around the pile is compacted and strengthened, therefore the friction at the "pile-soil" contact becomes higher. Therefore, in this case, the following coefficients were adopted: 1.15 for sandy soil, 1.05 for loam. After adjusting the friction at the contact, the convergence of the graphs presented in Figure 7, according to the results of the static test and the graph-analytical method increased.

In summary, the obtained values of the interface friction coefficient are consistent with those obtained by other authors. For example, Vasenin V.A. obtained a coefficient value of 1.0 for sandy soils and sandy loams, and 0.7 for loams for a bored pile. In their work, Sharafutdinov R.F., Razvodovsky D.E., and Zakatov D.S. obtained values of this coefficient for a bored pile in the range from 0.75 to 1.0. For piles driven without excavation, the value of the interface friction coefficient is highly dependent on density and ranges from 1.0 to 1.3 [Salnyi I.S., Pronozin Ya.A., and Karaulov A.M.].

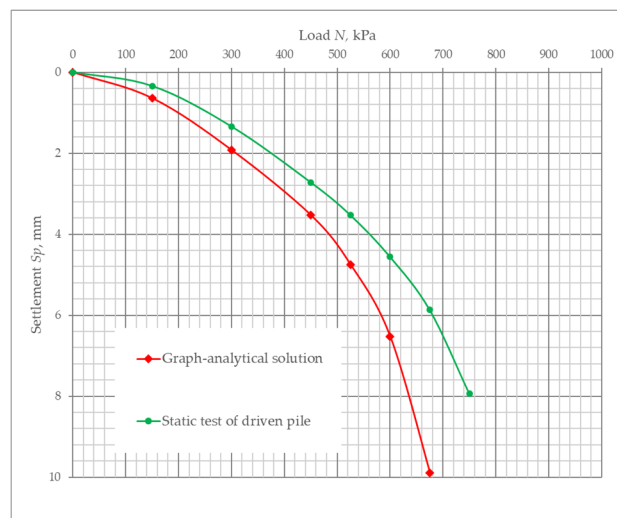


Figure 6. Graphs of settlement versus load of a driven pile without using the interface friction coefficients.

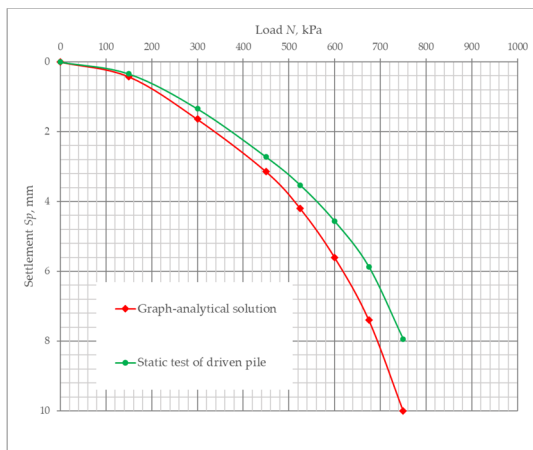


Figure 7. Graphs of settlement versus load of a driven pile with using the interface friction coefficients.

#### 4 CONCLUSIONS

1. This paper proposes an improved graph-analytical method for calculating the settlement of a single compressible pile interacting with a multilayer soil foundation with elastic-plastic properties. The modification of the graph-analytical method consists in taking into account the nonlinear soil behavior both on the side and at the tip of the pile, exhaustion of the soil bearing capacity in areas of the pile's lateral surface where the ultimate soil strength has been reached, redistribution of loads along the pile, and reduced friction at the pile-soil interface.

2. Verification of the proposed graph-analytical method with the results of a static test of a bored pile showed that without using friction coefficients that reduce the strength of the soils in the contact zone, the graphs have a similar deformation pattern, but the calculated values of settlement are less than the actual ones. Using friction coefficients of 0.9 for loams and 1.0 for sands made it possible to bring the calculated values of settlement obtained by the graph-analytical method closer to the actual ones.

3. Verification of the proposed graph-analytical method with the results of a static test of a driven pile showed a similar situation. However, since the driven pile is driven without excavating the soil, the soil around the pile is compacted and strengthened, therefore, the friction at the "pile-soil" contact becomes higher. Therefore, in this case, the following coefficients were adopted: 1.15 for sandy soil, 1.05 for loam. After adjusting the contact friction, the convergence of the static test with the graph-analytical method increased.

4. Thus, it can be concluded that it is important to take into account the technology of installing a pile in the ground, since it has a significant effect on the friction value at the pile-ground contact. For a more accurate prediction of the settlement of a single pile, calculated using the graph-analytical method, it is recommended to determine the friction coefficients empirically for each construction site. The friction coefficients can be determined based on the results of laboratory tests, or by reverse calculation based on the results of static tests of similar piles with similar engineering and geological conditions.

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