Consideration of parameters of underground structures interaction with soils when solving geotechnical problems

A Z Ter-Martirosyan, V V Sidorov, A S Almakaeva

REC "Geotechnics", Moscow State University of Civil Engineering (MGSU), 26, Yaroslavskoe shosse, Moscow 129337, Russia

E-mail: totilas96@mail.ru

Abstract. The article is devoted to determining the influence of the strength reduction factor on the interaction that occurs between the soil mass and underground structures. The objectives of this paper are the study of the strength characteristics at the contact of the soil and the material of the structure, the calculation of the strength reduction factor and application it in the numerical simulation of various geotechnical problems. Strength characteristics are obtained on direct shear apparatus. Concrete is used as construction material. The strength reduction factor is calculated as the ratio between the limit shear strength of the soil-concrete and the limit shear strength of the soil-soil. The results of numerical simulation show that when using interface elements and reducing the strength properties at the soil-concrete contact, the displacement of structures, as well as the forces arising in them, will change compared to cases where their interaction is not simulated. In reality, at the contact of the soil mass and underground structures there is a gap and slippage, and the use of interfaces allows more accurately taking into account these processes.

1. Introduction

The problem of interaction of building structures in the composition of retaining walls, bearing elements of tunnels, underground parts of buildings and structures, is widely studied in domestic and foreign geotechnical practice [1,2]. It is due to the fact that on the contact of the soil and structures there is a complex interaction between dissimilar materials. This leads to various phenomena, one of which is a decrease the strength characteristics at the contact, which can be taken into account by the strength reduction factor. It, in turn, is influenced by many factors, such as the type of soil, its density, humidity, size of soil particles, surface roughness, and the value of normal stresses. According to numerous well-known studies, humidity and relative surface roughness have the greatest effect on the strength reduction factor [3-6].

2. Literature review

The problem of the interaction of soils with various materials of construction was investigated not only in domestic practice, but also abroad. For example, in the work of Liming Hu and Jialiu Pu (2004) [7] shear tests were carried out on a steel plate with different roughness. In this paper, the conclusions were made that the destruction depends on the parameter of relative roughness, and the thickness of the soil shear zone was visually determined. Mohammadi, A, Ebadi, T, Eslami, A (2017) [8] investigated the effect of different concrete roughness on the shear resistance between sand and concrete and concluded that the angle of internal friction increases with increasing roughness of the
concrete surface. When testing clay soils with concrete Haeri, H; Sarfarazi, V; Zhu, ZM (2019) [9] concluded that in addition to roughness, the applied normal stress also affects shear resistance. According to the results of numerous studies, the values of the strength reduction factor were determined and ranged from 0.4 to 0.9 [10, 11]. Table 9.1 SP 22.13330.2016 «Bases of buildings and structures» presents a table of values of the strength reduction factor depending on the type of soil, its texture and degree of moisture.

3. Methods

Laboratory tests fine dry sands were performed with use direct shear apparatus. As an imitation of an underground structure, dies were used, cast from concrete, with a diameter of 71.4 mm and a height of 16 mm. After each test, concrete samples were rotated by 30° to ensure similar conditions to all tests, since sand particles scratch the surface, leaving furrows on it. Shear rate was 0.2 mm/min. The size of the gap was chosen so as to exclude the loss of particles from there: for small sands, the gap was set to 0.2-0.4 mm, and for large sands - 1 mm.

For presentation of the possible distribution of tangential stresses during shear in PLAXIS 2D 2018 a problem, simulating the direct shear test, was also solved. The soil sample is fine dry sand with an internal friction angle of 20° and cohesion of 1 kPa. Strength characteristics were determined by real laboratory tests. The soil is placed in a rigid steel holder with a fixed upper part. The shear of the lower part of holder was carried out by the applied horizontal displacements equal to 10.71 mm and the corresponding 15% shear deformations. The shear plane was modeled by the interface with the strength reduction factor of 1. This allows the lower part of the soil to shear relative to the top and by separating common grid points in the shear plane and not “pull” it along. A vertical load was applied to the specimen - 100 kPa.

When calculating geotechnical problems in specialized software systems, contact elements-interfaces are used to simulate the interaction on the contact of two dissimilar materials. The roughness of the contact surface is determined by the value of the strength reduction factor in the interface \( R_{inter} \), varying from 0, corresponding to an absolutely smooth contact, to 1, characterizing the surface as rather rough. When considering the interface in the tasks between the material of the structure and soil, there will be a gap and slip, due to which the structure will have greater freedom for movement. In the absence of contact elements in the task, soil and the structure will have common nodal points and, therefore, will move together, and the forces, deformations and displacements of the structure will not correspond to the real behavior. To determine the influence of \( R_{inter} \) on the forces arising in the structures, as well as on their displacement and deformation, three indicative tasks were calculated, designed in PLAXIS 2D 2018. Each task was calculated in 3 ways: without taking into account interfaces, with interface at \( R_{inter} = 1 \), and also with the interface at \( R_{inter} = 0.6 \). Characteristics of the interfaces were set by a separate material, while the specific adhesion was 0\((c = 0)\), and the angle of internal friction multiplied by the coefficient \( R_{inter} \).

4. Results and discussion

The results of laboratory tests for fine sands are presented in Table 1. The strength reduction factor \( R_{inter} \) is determined by the ratio of the limit shear strength of soil over concrete to the limit shear strength of soil to soil.

According to the test results with fine sand, the \( R_{inter} \) the strength reduction factor varies from 0.34 to 0.8, but most test results show the results of values \( R_{inter} \) in the range from 0.52 to 0.71. Getting six knocked out values can be explained by the ratio of particle size and gap. When shearing into the gap, several rows of particles fit in, therefore the shear occurs both on concrete and on the soil, which leads to an overestimated value of the limit shear strength [12]. However, as the size of the gap decreases, particles may become jammed. After rejecting the results, the average value of the obtained strength reduction factor is 0.6, which is consistent with that presented in Table 9.1. SP 22.13330.2016 «Bases of buildings and structures» is 0.67.
Simulation of the direct shear test showed that the average value of shear resistance arising along shear plane is 27 kN/m². The resulting value is close in value to that obtained during laboratory tests and is 27,9 kN/m². Figure 1 shows that a decrease friction resistance is observed along the edges of the sample, which is explained by the fact that the shear area in the device of direct shear does not remain constant, and the appearance of peaks is caused by the appearance of stress concentrators, which are manifested due to the PLAXIS program implementation.

| №  | $\tau_{lim}$ kPa | $R_{inter}$ |
|----|-----------------|------------|
| 1  | 28.8            | 0.58       |
| 2  | 28.5            | 0.67       |
| 3  | 28.5            | 0.61       |
| 4  | 27.0            | 0.52       |
| 5  | 27.5            | 0.71       |
| 6  | 27.9            | 0.57       |
| 7  | 27.9            | 0.58       |
| 8  | 27.9            | 0.58       |
| 9  | 27.9            | 0.67       |
| 10 | 27.9            | 0.61       |
| 11 | 27.9            | 0.60       |
| 12 | 27.9            | 0.52       |
| 13 | 27.9            | 0.34       |
| 14 | 27.9            | 0.37       |
| 15 | 27.9            | 0.37       |
| 16 | 27.9            | 0.37       |
| 17 | 27.9            | 0.34       |
| 18 | 27.9            | 0.8        |

Figure 1. Shear stress distribution [kN/m²]:
(a) along the shear plane, (b) the height of the sample.

In the 1st task, a pit with reinforced concrete wall and a thrust system was designed to determine the effect of the strength reduction factor on the internal forces arising in it. From the plots of bending moments that occur in the pit of wall at the time of its full excavation, you can see that with the advent of the interface and the decrease in strength characteristics at the soil-to-wall contact, the bending moment increases, although its change in wall height is uneven, but the maximum bending moment values increase by 25%.
Figure 2. Bending moments of reinforced concrete pit fencing: (a) without interfaces, (b) with interface ($R_{inter} = 1$), (c) with interface ($R_{inter} = 0.6$).

In the 2nd task, a single reinforced concrete pile with a load of 100 tons applied to it was considered. According to the calculation results, the change in pile settlement was determined depending on the account of the contact element and its set of characteristics. In Figure 2 you can see that the precipitations in the problem without interfaces on the contact pile-soil and in the problem with the formulation of the contact element with $R_{inter} = 1$ are almost equal, as evidenced by the proximity of the lines of these curves, and the graph of the curve obtained in the 3rd stage of calculation deviates from others, and the difference between precipitation is 4%. However, more importantly, the exhaustion of lateral capacity and the failure of the pile occurs at different levels of the applied load. Taking into account the interface and reducing the strength characteristics at the contact, the lateral capacity of the pile is reduced.

Figure 3. (a) Calculation scheme, (b) graphs of dependence of the change in the settlement of a single pile from the load.

In the third task, the horizontal displacements were determined, caused by the horizontal pressure of the soil on the retaining wall. Figure 3 shows the graphs of the horizontal displacement of the retaining wall as a function of the horizontal pressure without and taking into account the interface with the specified strength reduction factor $R_{inter} = 0.6$. The maximum horizontal displacement in the
1st case was 22.9 mm, and in the 2nd case – 24.4 mm. The difference is only 6%, but it must be borne in mind that with greater horizontal pressure the difference between the values can be much greater.

![Figure 4: (a) Calculation scheme, (b) graphs of horizontal displacement versus landslide pressure.](image)

Summarizing, we can say that when solving geotechnical problems, it is necessary to take into account interface elements with a correctly specified strength reduction factor, since in reality the shear resistance at the soil-structure contact will be less than that at the soil-soil contact, respectively slippage, detachment and movement corresponding to the contact parameters may occur on the contact of materials.

5. **Conclusion**

1. Laboratory tests of a direct shear of a concrete sample on soil showed a large scatter of the values of the limiting shear resistance, which is explained by the fact that the process itself is sensitive to the size of the gap. Therefore, its value should be selected depending on the grain size. If the gap is smaller than the size of the soil particle, then they will jam, preventing the formation of some contact layer involved in the work. But if the gap is larger, then several rows of particles will fit into it, as a result of which the shear will occur both on the concrete surface and on soil.

2. Numerical simulation of the direct shear test showed a possible picture of the distribution of tangential stresses; moreover, the average value of shear resistance agrees well with the value obtained during laboratory tests. However, stress concentrates may occur at the sample end.

3. Numerical simulation showed that when using contact elements with regard to reducing the strength characteristics, the values of internal forces or displacements of structures increase, which significantly affects the further design of these structures in terms of reinforcement and material selection.

4. In addition to the strength reduction factor, it is necessary to take into account the thickness of the soil shear zone (interface thickness), but at the moment this topic has little knowledge in international scientific practice, which makes it interesting for further research.

**Reference**

[1] Saberi M, Annan C-D and Konrad J-M 2018 On the mechanics and modeling of interfaces between granular soils and structural materials *ACME* 18 1562–79
[2] Jiang S, Du C and Sun L 2018 Numerical analysis of sheet pile wall structure considering soil-structure interaction Geomech. and Eng. 16 309–20
[3] Di Donna A, Ferrari A and Laloui L 2017 Experimental investigations of the soil-concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures Can. Geotech. J. 53 659–72
[4] Ilori A O, Udoh N E and Umene J I 2017 Determination of soil shear properties on a soil to concrete interface using a direct shear box apparatus IJGE 8
[5] Chen X B, Zhang J S; Xiao Y J and Li J 2015 Effect of roughness on shear behavior of red clay – concrete interface in large-scale direct shear tests, Can. Geotech. J. 52 1122–35
[6] Xu Z H, Zhang G D, Liao W, Liao A M and al. 2016 Study on mechanical behaviors of interface between gravel soil and concrete with large-scale simple shear test JAER 78 547–51
[7] Hu L M and Pu J L 2004 Testing and Modeling of Soil-Structure Interface JGGE 130 851–60
[8] Mohammadi A, Ebadi T and Eslami A 2017 Shear strength behavior of crude oil contaminated sand-concrete, interface Geomech. Eng. 12 211–21
[9] Haeri H; Sarfarazi V and Zhu Z M 2019 Investigation of shear behavior of soil-concrete interface Smart Struct. Syst. 23 81–90
[10] Hisham T, Eid, Ruslan S, Amarasinghe, Khaled H, Rabie and Wijewickreme D 2015 Residual shear strength of fine-grained soils and soil–solid interfaces at low effective normal stresses Can. Geotech. J. 52 198–210
[11] Potyondy J G 1987 Skin friction between various soils and construction materials Géotechnique 37 339–53
[12] Du P, Liu X L and Yang B 2015 Numerical Simulation Study on the Failure Mode of Soil-structure Contact Interface JAER 15 426–29