Soil and structure interaction investigation features

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Abstract. The interaction of soils with underground structures is an important and complicated geotechnical problem, because a new stress-strain state is formed on their contact, associated with reduced strength properties of soils. To determine these characteristics, laboratory tests by direct shear scheme with stiff clay and loam interacting with a concrete surface were carried out. Soil samples were taken from a depth of more than 35 m in Moscow. The tests were carried out according to the "soil-soil" and "soil-solid surface" schemes with a speed of 0.005 mm/min for clay and 0.05 mm/min for loam. According to the results of laboratory tests, strains and deformations were obtained. Also, the strength reduction factors were determined equal to 0.53 for clay and concrete and 0.44 for loam and concrete. This coefficient is one of the main parameters characterizing the magnitude of decrease of the strength characteristics at the contact in numerical calculations. Moreover, two methods for modeling the contact zone of the soil massif and a single pile were considered in the PLAXIS 2D software package. In the first case, the problem was modeled with use special contact elements “interfaces”, which have zero (virtual) thickness, and in the second case, the contact zone was defined by a layer of soil of real thickness, for which the properties are equivalent to the properties of the virtual interface. The results of numerical modeling showed that the shear stresses on the contact in the case of a real interface will be less than when using a virtual interface, and the bearing capacity of the pile will decrease by almost 2 times.

1. Introduction
The problem of the interaction of soils and structures is widely studied abroad, however, in Russia this topic is not addressed so often, although it plays an important role in geomechanics. Many studies of shear strength at the contact of soils and various structural materials show a large fragmentation of the results. The reason for this is that the contact strength depends on many parameters, which it is not possible to fully take into account [1-6]. This applies both to a theoretical solution and to a numerical one, solved by computer simulation. That is, the difficulty concludes not only in conducting laboratory tests and processing the obtained data, but also in the method of modelling the interaction of two different materials, which are associated with the calculation features in specific geotechnical software complexes [7].

2. Literature References
A significant number of tests show that the obtained strength characteristics depend on various parameters, such as the type of soil, its particle size, humidity, density, relative roughness, material of solid surface, normal stresses, the type of device in which the tests are carried out, etc. This influence was considered in 2015 by H.T. Eid et al. [8], where various tests were carried out between clay and
steel plates with different roughness. They concluded that the residual shear strength decreases with increasing liquid limit, fractions of clay particles and a decrease the roughness of the steel plate. Moreover, liquid limit has a greater effect on the strength than the fraction of clay particles. Similar researches which studying the effect of roughness were carried out earlier, for example, in 2006 F. Hammoud and his colleague [9] performed a series of tests on a torsion shear device. Also, A. Mohammadi et al. in 2017 [10] investigated the effect of various roughness of a concrete surface on the shear resistance between sand and concrete in a direct shear device. In another article, N. Haeri, with colleagues [11], when testing clay with concrete, it was noted that, in addition to roughness, the applied normal stress also affects shear resistance [12]. This difference in the results is explained by a different mechanism of destruction, because with a in-plane shear, the soil is cut along a fixed horizontal plane, and with a simple shear, destruction occurs along several shear planes. Y.S. Tsubakihara et al. came to the same conclusions in 1993 when testing sea clays with steel plates in similar instruments [13]. Pile installation influence has a significant impact on the formation of the stress-strain state on surrounding soil, but this factor wasn’t considered in this study of problems. This is due to the fact that this is a separate large scientific and technical direction, which needs to be studied more carefully the availability of additional equipment.

Many studies have explored the strength reduction factor, which is defined as the ratio of the shear peak or residual strength at the contact between the soil and a solid surface to the shear peak or residual strength of this soil. The obtained values of the strength reduction factor ranged from 0.4 to 0.9 [14-15].

In article I.P. Damians et al. [16] presented the results of numerical calculations of normal and shear stresses at the contact of piles and soil massif, where the contact was modeled with a zero thickness interface and a real interface of equivalent thickness. These calculations showed that both methods can be used in solving problems, but in the case of using the real interface when the plastic stage is reached, the distribution graph of normal and shear stresses starts to fluctuate with depth, while when using the zero thickness interface it does not have amplitude vibrations, i.e. has a "smooth character".

3. Methods
To compare the strength characteristics of soils, as well as the strength characteristics that arise at the contact of soils with various materials, and to determine the strength reduction factor, a direct shear device was used in this study [17]. Sample preparation and testing were carried out in accordance with GOST 12248-2010 "Soils. Laboratory methods for determining the strength and strain characteristics".

The principle of operation of a direct shear device is that the shear occurs due to shear loading of the movable part of the box relatively stationary when a vertical load is applied to the sample. Due to the gap formed between the two parts of the box, the horizontal plane of the shear is fixed. When conducting the test according to the “soil-solid surface” scheme, the gap size can have a significant effect on the strength characteristics, since during shear the layers of soil particles involved in the work create additional shear resistance, i.e. the shear occurs not only on solid material, but also on the soil. The more the cohesion of the particles of the tested soil sample, the less this phenomenon appears [18].

Stiff clay and loam were selected from the Fili-Davydkovo district of Moscow during the construction of the metro station. Loams were taken from a depth of 36 m, and clay from a depth of 40 m. Test specimens were cut from monoliths of natural humidity to the size of the box of the device: with a diameter of 71.4 mm and a height of 35 mm. During the test according to the “soil-concrete” scheme, a concrete sample was placed in the lower part of the box, and in the upper part of the box was a soil sample so that the contact zone of two materials fell into the formed gap. Before testing the soil with concrete, the contact surface of the soil sample was leveled with a sharp knife before the start of the experiment.

The gap between the movable and fixed parts of the shear box was set the same for all tests - 0.6 mm. Its value was selected so that the lower and upper parts of the box did not touch each other to
exclude the occurrence of additional friction, as well as taking into account the absence of extrusion of soil into the gap at vertical pressure. In order to ensure the outflow of water from the pores of the soil sample, its ends on both sides were covered with a paper filter and a filter stone, and when tested with concrete, one side only. Next, a stamp was installed on top, through which the vertical pressure is transmitted. LVDT sensors measuring vertical and shear deformations were brought into working position and adjusted before each test after the assembly of the direct shear device was completed.

The shear was carried out according to the scheme of consolidated-drained (slow) shear, i.e. first, each soil sample was preconsolidated for eight hours with a vertical load of 100 kPa in the device itself before the start of the experiment. After specimen preconsolidation process it was loaded with lateral pressure with a constant vertical value $\sigma_n = 100$ kPa of constant speed, determined depending on the plasticity index $I_p$. The main physical properties and the shear rate at which the tests were carried out are given in table 1. The shear was carried out until the shear strain reached 15%.

**Table 1. Physical properties of soil and shearing rate**

| Name of soil | Humidity of the lower plastic limit $W_{pl}$, % | Humidity of liquid limit $W_{li}$, % | Plasticity index $I_p$ | Shear rate $V$, mm/min |
|--------------|-----------------------------------------------|-----------------------------------|-----------------------|-----------------------|
| Clay         | 45                                            | 90                                | 0.45                  | 0.005                 |
| Loam         | 28                                            | 44                                | 0.16                  | 0.05                  |

The interaction between the soil massif and the underground structure was simulated in two ways in the PLAXIS 2D software package using the example of a single pile and soil massif interaction problem. Numerical calculations were carried out to determine the degree of influence of the application of the strength reduction factor in the interface elements on the stress-strain state of the base, to obtain a qualitative result of the distribution of shear stresses on the side surface of the pile.

In the first case, the interaction was set using special contact elements called “interfaces”, the principle of which is that they can be used to divide common nodal points at the contact of underground structures and adjacent soils. This allows the structures to move, slip and deform separately from the adjacent soil. The interface element has two main parameters: the strength reduction factor ($R_{\text{int}}$) and virtual thickness of the shear zone ($\delta_{\text{int}}$). The first parameter affects the shear strength of the “interface” layer by reducing the strength characteristics of the soil and varies from 0 to 1, which corresponds to a fraction of the maximum strength value. The second parameter describes the thickness of this soil layer at the contact involved in the shear and movement of the construction, which has properties that are different from the soil. Since not only the first (contact) layer of soil particles is involved in the work during shear, but also the following layers interacting with the latter, it can be assumed that the larger the thickness of the soil will interact with the underground structure than the higher the shear resistance realized. Consequently, the strength characteristics at the contact of the soil massif and the structure will also be higher. For all calculations, the value of the strength reduction factor was taken equal to 0.67. The virtual thickness corresponds to the real thickness of the shear zone and is determined by the formula:

$$\delta_{\text{int}} = \delta_{\text{virt}} \cdot A$$  \hspace{1cm} (1)

where $\delta_{\text{virt}}$ – virtual thickness coefficient, varying from 0.01 to 1;
$A$ - average size of elements, m.

In the second case, the interaction was modeled using an interface of real thickness, which was set in the form of a layer of soil with properties and thickness corresponding to the virtual interface. The properties of the real interface were calculated on the basis of formulas embedded in the software package for calculating the strength and deformation characteristics of the virtual interface:

$$\nu_i = 0.45$$  \hspace{1cm} (2)
\[ c_i = R_{\text{inter}} \cdot c_{\text{soil}}, \]  
\[ \phi_i = \tan^{-1}(R_{\text{inter}} \cdot \tan \phi_{\text{soil}}) \]  
\[ G_i = R_{\text{inter}}^2 \cdot G_{\text{soil}}, \]  
\[ E_{\text{ed,1}} = \frac{2G_i}{1-V_i}, \]  

where \( \nu_i \) – Poisson's ratio; \( c_i \) – cohesion of interface, taken equal to 0 in accordance with table 9.1 of SP 22.13330.2011 “Soil bases of buildings and structures”, kN/m²; \( c_{\text{soil}} \) – soil cohesion, kN/m²; \( \phi_i, \phi_{\text{soil}} \) – the angle of internal friction of the interface and soil, respectively, deg.; \( \psi_i, \psi_{\text{soil}} \) – the dilatation angle of the interface and soil, respectively, deg.; \( G_i, G_{\text{soil}} \) – shear module of interface and soil, respectively, kN/m²; \( E_{\text{ed,1}} \) – interface compression module, kN/m².

To study the influence of the contact simulation method on shear strains were accepted the following virtual thickness values of 0.05, 0.1, and 0.5 and the corresponding real thickness values, determined by formula (1) as 51 mm, 102 mm, and 510 mm. However, it is worth noting that the virtual thickness of the shear zone depends on the virtual thickness coefficient, and recommendations for choosing its specific value are not given in the manual of the software package used. Figure 1 shows the calculation schemes for modeling the contact zone.

![Figure 1](image)

**Figure 1.** The calculation scheme of the problem for various methods of modeling the contact zone: with a virtual interface (a), with a real interface (b).

4. Results

According to the results of laboratory tests of soils, graphs of the dependence of shear stresses on absolute shear strain the curve \( \tau = f(d) \) were obtained.

Figure 2 shows the clay test curves labeled “DS”, which means “direct shear” followed by a number indicating the test number. With a shear of 1 ... 2 mm, soil samples reached their limit state, and then a collapsing occurred. According to pronounced peaks, it can assume that the nature of the destruction is fragile. The obtained values of ultimate shearing resistance are in the range from 100 to 165 kPa. The wide spread of the test results is probably due to the fact that the shear occurred not only along a fixed horizontal plane, but also along the cracks of soil samples formed during the test, as on the most weakened surfaces. Since the value of shear strength is significantly affected by the nature of
the roughness of the walls of the cracks, the obtained values of the peak shearing stresses vary over a wide range of values [19-20].

![Figure 2. Curves of shearing strain versus linear displacement $\tau = f(d)$.](image)

In the case of the “DS2” curve, two peaks are visible in the graph: the first peak value of the shear resistance was obtained when the shear occurred, and the second peak occurred when the dilatancy appeared during the shear.

Figure 3 presents the results of shear tests for clay and concrete. The shear occurred at a linear displacement of 1-2 mm, the limit values of shear resistance vary from 55 kPa to 80 kPa. The dispersion of the values turned out to be less than during the test according to the "soil-soil" scheme, because the surface of clay samples was prepared for testing and had no roughness. In addition, the values of ultimate shearing resistance were lower than when testing samples of clay. The obtained result only confirms the fact that the shear strength in the contact zone is lower than in an ordinary soil massif.

![Figure 3. Curves of shearing strain versus linear displacement $\tau = f(d)$.](image)
Figure 4 shows the test curves of loam. This graph shows that the spread of the peak values of the shearing stresses and the nature of the curves have poor convergence with each other. Since these samples have layers of loam with a more plastic consistency, the destruction of the samples is of a different nature. In addition, there are inclusions of belemnites in these loams, which repeatedly fell into the shear plane, and, as a result, a second peak appeared on the graphs. The ultimate shearing resistance varies in the range of 100 ... 160 kPa. The second peak has the curves “DS1”, “DS2” and “DS4”.

![Figure 4. Curves of shearing strain versus linear displacement \( \tau = f(d) \).](image)

Less dispersion of the values of ultimate shearing resistance are obtained when testing loam with concrete: from 50 kPa to 80 kPa. The values, as well as the values of the test results of clay samples, were lower than the tests on the soil-soil testing scheme. Figure 5 shows that failure occurs when the shear deformation is 1 mm. The nature of the curves have a similar repeatability, except for the curve "DS1", which has a peak. Such a deviation may be due to the presence of belemnite inclusions in the sample, which can interact with irregularities of the concrete surface and provide additional shear resistance.

![Figure 5. Curves of shearing strain versus linear displacement \( \tau = f(d) \).](image)
Table 2 shows the values of ultimate shearing resistance during testing of clay with concrete and the strength reduction factors. The obtained values of the strength reduction factor $R_{\text{inter}}$ varies from 0.47 ... 0.57. The average value $R_{\text{inter}}$ at the contact between clay and concrete was 0.53.

| №  | Soil-soil $\tau_{\text{max}}, \text{kPa}$ | Soil-concrete $\tau_{\text{max}}, \text{kPa}$ | The strength reduction factor $R_{\text{inter}}$ |
|----|-----------------------------------|---------------------------------|-------------------------------|
| 1  | 164.30                           | 76.40                           | 0.47                          |
| 2  | 147.90                           | 75.90                           | 0.51                          |
| 3  | 130.40                           | 74.90                           | 0.57                          |
| 4  | 124.90                           | 70.60                           | 0.57                          |
| 5  | 117.70                           | 62.00                           | 0.53                          |
| 6  | 104.50                           | 55.20                           | 0.53                          |

Similar results of testing loam with concrete are given in table 3. The obtained values of the strength reduction factor $R_{\text{inter}}$ varies from 0.39 ... 0.49. The average value of $R_{\text{inter}}$ at the contact between loam and concrete was 0.44.

| №  | Soil-soil $\tau_{\text{max}}, \text{kPa}$ | Soil-concrete $\tau_{\text{max}}, \text{kPa}$ | The strength reduction factor $R_{\text{inter}}$ |
|----|-----------------------------------|---------------------------------|-------------------------------|
| 1  | 158.40                           | 76.40                           | 0.48                          |
| 2  | 143.20                           | 63.40                           | 0.44                          |
| 3  | 139.60                           | 56.50                           | 0.40                          |
| 4  | 132.30                           | 52.00                           | 0.39                          |
| 5  | 121.30                           | 51.60                           | 0.43                          |
| 6  | 97.60                            | 47.70                           | 0.49                          |

According to the obtained values of the strength reduction factor we can say that the strength at the contact between concrete and clay is slightly lower than at the contact of concrete and loam. This phenomenon can be explained by the fact that the strength at the contact depends on the angle of internal friction of the soil, therefore, with a decrease in the content of clay particles and an increase of the sand particles number, the angle of internal friction increases, and, consequently, the strength at the contact of soil and concrete also grows [7]. The obtained average values of $R_{\text{inter}}$ during laboratory tests are similar to the value presented in table 9.1 SP 22.13330.2016 (Russian normative document) and equal to 0.5 for all soils of natural moisture at the contact with concrete.

The received values of the strength reduction factor of the interface elements were used for numerical modeling on the example of the problem of the interaction of a single frictional pile with a homogeneous soil massif. The purpose of the calculations was to show the degree of influence of the applied factor on the stress-strain behavior of the foundation soil.

Figure 6 showed that modeling the contact of a certain layer of material of real thickness with the specified equivalent properties of the virtual interface leads to the fact that the distribution of shear stresses along the length of the pile began to oscillate after the transition of the soil to a plastic state at the contact. That is, modeling the interaction of the soil massif and a single pile using contact elements of virtual thickness shows a more uniform distribution of shear stresses. According to studies [2], the pressure fluctuations will be the greater, the higher the stiffness of the contact zone. According to the graphs of the curves constructed using the virtual interface, it can be noted that with an increase in the value of the virtual thickness coefficient, the value of shear stresses in places with the highest plastic deformations changes.
Figure 6. Curves of the distribution of shear stresses at the contact of the pile with the soil mass along its length.

In addition, the plot shows that problems with a virtual interface the values of shear stresses along the entire length of the pile are less than in problems with a real soil layer of the interface zone. Therefore, figure 7 presents graphs of the dependence of settlement on load, constructed for an interface with a thickness of 102 mm, which showed that modeling a contact with a real interface, pile failure occurs when a load is transferred equal to 0.57 in fractions of the applied vertical pressure on the pile, and in the case of a virtual interface pile failure occurs when the load is equal to 0.99 of the full value. Pile failure in the first case occurs at a load almost 2 times less than the second case, therefore, their bearing capacity differs by 2 times. In addition, the bearing capacity of the piles for both methods at a load not exceeding 0.57 in fractions of the total applied load to the pile is the same, as evidenced by the proximity of the lines of these curves.
5. Conclusions
1. Laboratory tests of direct shear of clays showed a rather large scatter of the shear strength limit values and the different nature of curves of the shear stress variation during the test.
2. The tests for loams showed that the destruction, the nature of the curves and the peak values of the shear stresses depend on the homogeneity of the test specimen, since the shear passes along a fixed horizontal plane, depending on the design of the device. In the shear plane there may be solid inclusions or interlayers of soils with strength characteristics different from the main material of the sample.
3. The results of direct shear tests for clay and loam on concrete showed that the spread peak values of shear resistance is less than when testing only clay or only loam, since the shear plane of the sample was specially prepared for each test. Due to the fact that the peak values of shear resistance were also smaller, the strength in the contact zone will decrease.
4. The calculated the strength reduction factors $R_{\text{inter}}$ for the contact of clay with concrete and loam with concrete are close to the value of the factor presented in SP 22.13330.2016. But it is worth noting that in order to apply a more accurate the strength reduction factors $R_{\text{inter}}$ in engineering practice, especially with regard to high responsibility structures, it is necessary to perform at least 6 tests for each specific construction site. However, to obtain general results for describing the interaction of sand and clay soils with various building structures and their interpretation in the form of visual technical material (tables, diagrams, nomograms, etc.) for more convenient engineering use, it is necessary to analyze more test results.
5. The results of numerical simulations showed that when a contact zone is defined by a layer of soil of real thickness with characteristics equivalent to a virtual interface, the values of shear stresses along the length of the pile on the distribution curve change at certain intervals when the soil adjacent to the pile transitions to a plastic state.
6. When using interfaces of real thickness, the values of shear stresses turn out to be less than when using virtual interfaces. This is probably due to the fact that the pile is faster exhaustion of bearing strength. Since the choice of a specific method for modeling the contact zone of the soil mass and the
structure affects its strength, further selection of the material of the structure and its design features will depend on this.

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