The terms of soils removal from the defects of the underground structures’ lining

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Abstract. The lack of filtration reliability of bearing structures of urban underground facilities laid down at the design stage is associated with the unresolved issues of their filtration interaction with the adjacent soil or rock body. Water flows through the lining of the underground structure destroy the load-bearing structures, contribute to the removal of loose material into underground workings and create unacceptable microclimatic conditions for human stay. The question arises not only about the permissible degree of permeability of these structures, about the influence of filtration processes on the properties of the lining materials and their stability, but also about the relationship of water permeability of the bearing elements with the properties of the rock mass. Therefore, ensuring the filtration reliability of urban underground structures should be based on a set of protective measures aimed at involving in the work of the relevant properties of the underground object, and rock mass and technological methods of its construction, maintenance and operation. The problem of sealing the underground structure cannot be solved only by improving the concrete lining and raises the question of the need for measures to manage the characteristics of the state of the soil mass, which is the subject of this study.

1. Introduction
Construction and operation of underground structures is often accompanied by the formation of significant defects in their lining [1,2], in a short time leading to the failure of objects and major risk to other structures and buildings in the close vicinity [3-5]. Repairs at the same time are from 25 to 100 % of the cost of construction of the underground structure. Opening of the mechanism of formation of lining defects allows developing actions for prevention of their formation, reduction in cost of operation and construction of underground facilities in the city. As the main role in the defects formation is played by filtration processes, they should be most carefully considered from the position of the cause of leaks in the bearing structures of underground facility. The solution to the problem of providing a filtration reliability of underground structures requires a quantitative estimate of the probability of leaks, and, consequently, determine the allowable filtration rate of the local loose sections of concrete lining of underground structures. Reliability indicators of underground structures are currently at a low level. Underground structures of the city are placed most often in sediments, represented by sands, sandy loams, loams and clays. The removal of these soils through defects in the lining of underground structures is the result of complex processes associated with the filtration effect on the soil. In this case, there is a process that is not actually a suffusion (if we understand by it the removal of small mineral particles and soluble substances by water filtered in the thickness of the soil massif), and can be so called somewhat conditionally [6-8]. It is known [6, 9-13] that soils acquire fluidity in the watered state, both under the influence of dynamic forces and under static conditions. In the first case, there is a filtration destruction of soils, in the second – its liquefaction.
2. Conditions for quicksand and pseudo-quicksand formation

Filtration destruction of soils in static conditions is especially strong where the watered soil is affected by factors, leading to its quicksand. True quicksand [6] is associated with a special physical and chemical state of interaction between water and soil, in which the mixture passes into an unprovoked fluid state. At a certain degree of dispersion of sand in the presence of colloids of clay and other substances, solid particles are weighed in water, separated from each other by films. Water in films under high pressure (more than 1000 MPa), due to the influence of electro-molecular forces, acquires an increased density (more than 1 kg/m³). The density of water, which is close to the density of a solid body, provides, by virtue of Archimedes' law, a significant weighing effect, and a mixture of soil and water flows as a result of which, i.e. a quicksand is formed.

In addition to quicksand, there are pseudo-quicksand [2,6], which also remove due to the loss of internal friction and the weighing of particles in the water. The condition for the formation of pseudo-quicksand is the critical pressure gradient $I$, at which the rock passes into the quicksand, and the critical porosity of the soil.

The critical porosity of the soil (sand) is such a value of its porosity, at which there are no changes in the volume of sand during shift, i.e. the critical porosity serves as the boundary between the dense and friable state of the soil.

The critical gradient of the pressure $I_k$ for pseudo-quicksand is determined by the formula:

$$I_k = \frac{\nu - 1}{1 + \varepsilon},$$

where $\nu$ – the relative density of the rocks; $\varepsilon$ – porosity coefficient.

Coarse-grained rocks cannot flow as quicksand or pseudo-quicksand, but under certain conditions they “liquefy” and move easily in space. Most often, sands that have reached critical porosity pass into the liquefied state. Thus, liquefaction is a kind of pseudo quicksand of soils. At the same time, if the sands are clean, the liquefaction is accompanied by their compaction even under dynamic conditions, and only significant dynamic accelerations lead again to the liquefaction of the sand. Sand contaminated with clay and other colloidal particles increases its fluidity due to the phenomenon of thixotropy. Thixotropic properties can be manifested in sands and loams, containing a sufficient number of colloids with a high structure-forming ability.

Thixotropic structure formation depends on a number of factors [1,14]:
- quantity, composition, shape and structure of highly dispersed particles;
- composition, structure and activity of organic matter;
- mineralization of pore solutions;
- composition of exchanged cations in soils and a number of other factors.

Consequently, sandy soil contaminated or uncontaminated with clay particles can acquire mobility with simultaneous loss of load-bearing capacity as a result of the phenomena of quicksand, pseudo-quicksand, liquefaction and thixotropic soil destruction. All these factors often work together, if there is a filtration through the ground of groundwater with sufficient pressure.

3. Mechanical suffusion conditions

Suffusion is the process of loosening sands, even those that do not contain soluble components, by filtering through them with a flow, as a result of the removal of the smallest grains. Mechanical suffusion is possible under one of three conditions. The first condition occurs when the soil is composed of particles of different diameters, and minimum diameter of the soil particles $d_{\text{min}}$ is equal to or less than the diameter of the filtration passages-pores $d_n$ in particles of large diameter, that is

$$d_{\text{min}} \leq d_n.$$  (2)

This is true if the diameter of the grains of a larger fraction exceeds the diameter of the adjacent fraction by more than 20 times:

$$D/d > 20.$$  (3)
Another condition for the removal of small particles from the soil is the turbulent water pressure in the pores, defined as the excess of the pressure gradient $I > 5$ [9]. The third condition for the removal of particles is the possibility of a suffusion at the contact of two layers, when the ratio of rock filtration coefficients in these layers is greater than 2; an example is the contact of clay and sand layers.

The removal of the destroyed soil particles into the inner space of underground structures leads to the development of their lining defects “fistula”. Since the bulk of the “fistulas” is confined to the lower part of the tunnel section, the removal of soil through them occurs in the upstream flow, where the filtration destruction of the soil and the removal of particles are possible if the pressure gradient is determined by the following expression [9]:

$$ I_v = 4.5 \left( \frac{d_e}{d_a} \right)^2, \tag{4} $$

where $d_e$ – the estimated diameter of granules, mm; $d_a$ – the average diameter of the pores in the rock, mm. The estimated pore diameter in the rock is determined from the expression:

$$ d_e = \frac{1.9 \sqrt{\gamma}}{\sqrt{\Delta - \gamma}} \sqrt{U_d \Delta}, \tag{5} $$

where $\Delta$ – density of rock particles, g/sm$^3$; $\gamma$ – average density of filtration flow water, g/cm$^3$; $U_d$ – destructive rate of filtration in the pores of the rock, cm/s,

$$ U_d = V_d / n', \tag{6} $$

$V_d$ – destructive flow rate, determined empirically, cm/s; $n'$ – the actual porosity of the rock, equal to:

$$ n' = n \left( 1 - 0.114 \frac{1 - n}{n} \right), \tag{7} $$

$n$ – porosity, determined experimentally.

The average pore diameter in the rock is calculated by the formula:

$$ d_0 = 3.1 \sqrt{K_d \gamma}, \tag{8} $$

where $K_d$ – average rock filtration coefficient, cm/s; $\gamma$ – dynamic water viscosity coefficient, cm$^2$/s.

The critical velocity $U_d$, the excess of which entails the suffusion removal of particles, is determined by the formula of Abramov [1]:

$$ U_d = 60 \sqrt[12]{K_f}, \tag{9} $$

where: $K_f$ – rock filtration coefficient, cm/s.

The described mechanism of suffusion is typical for soils where particles are in simple contact with each other. In the presence of small and fine particles of colloidal type in the soil and some connectivity, there is a kind of internal erosion of the rock. If rocks such as clays, loess, etc. have cracks and large pores, the walls of these leaks are destroyed with the formation of cavities and channels. In contact filtration of unstable rock with waterproof, occurs contact suffusion. The speed of water at the same time, when filtering from the bottom up, is determined by the formula of Izbash [2]:

$$ V_d = V_0 + \frac{d^2}{D} f, \tag{10} $$

where $V_0$ – the rate of filtration, which is overcome by the weight of sand; $d$ – diameter of grains smaller fractions; $D$ – diameter of grains larger fraction; $f$ – function of the coefficient of friction.

Experimentally, the formula (9) was transformed by Kozlova [9] into the following:

$$ V_d = 0.26d^2 \left[ 1 + 1000 \frac{d_0}{D_0} \right], \tag{11} $$

where $d_0$ and $D_0$ – the size of the particles of sand and gravel layer, less than which the soil contains 60 % of the sum of all particles.
The described mechanism of suffusion destruction of soils in conditions of pressure watering allows us to evaluate the properties of soils containing urban underground structures. The tendency of soils to filtration failure is determined by the pressure gradient and critical filtration rates (formulas (3), (8)). For inhomogeneous soils, these values can be taken according to Volodko, given in table 1.

Table 1. Values of critical velocities and critical filter gradients

| Grain diameter, mm | The critical filtration velocity, $V_d$ m/day | Critical filtering gradient $I_d$ |
|-------------------|---------------------------------------------|----------------------------------|
| 0.57              | 890                                         | 6.67                             |
| 0.90              | 530                                         | 1.63                             |
| 1.35              | 300                                         | 0.54                             |

When the structure of the adjacent rocks is more complex, a colloidal-mechanical suffusion is observed, manifested in the removal of the smallest particles through the voids of large ones. This phenomenon is especially characteristic on contact of filtration-unstable soils with waterproof: pebbles, hard fractured or karst rocks (formulas (9), (10)). According to D. Justin's calculations, the value of the erosion velocity of gravel and sand particles takes the values presented in the table 2. Data of table 2 are characteristic of homogeneous, idealized soil. There are no such indicators for real soils containing urban underground structures, but the previously described method allows such an assessment, based on data on the physical and mechanical properties of soils.

Table 2. Values of erosion velocity of sand and gravel particles

| Particle diameter, mm | Critical speed m/minute | Critical speed sm/s |
|-----------------------|-------------------------|---------------------|
| 5.00                  | 13.23                   | 22.1                |
| 3.00                  | 10.37                   | 17.3                |
| 1.00                  | 5.91                    | 9.85                |
| 0.50                  | 5.30                    | 8.83                |
| 0.30                  | 4.18                    | 6.97                |
| 0.10                  | 1.83                    | 3.05                |
| 0.05                  | 1.31                    | 2.19                |
| 0.01                  | 0.59                    | 0.98                |

4. Soil liquefaction
Liquefaction is a kind of pseudo-quicksand of soils. Mainly Sands are subject to liquefaction. When liquefied, sand is like a thick viscous liquid, with virtually zero shear strength due to the lack of contact between grains separated by water shells. The liquefaction of the sands takes place, with the simultaneous manifestation of the following factors:
- destruction of the structure,
- the ability of the sand to be compacted,
- water saturation of sand.

The reason for the destruction of the sand structure in the water-saturated state can be dynamic load (shock or vibration) applied to it.

The most part of urban underground structures, are the workings of shallow laying, which causes the impact of dynamic loads of vibration type in combination with the initial statically stressed state on them. In work [6] as a criterion of intensity of influence at vibration loadings the acceleration of oscillations defined from the equation is offered:

$$\eta = A \cdot \omega^2,$$

where $A$ is the amplitude of oscillations; $\omega$ is the frequency of oscillations.

The value $\eta$, is usually determined experimentally, the relationship between it and the average density or porosity coefficient is graphically (figure 1).
To simplify the calculations, the sand compaction coefficient at vibration or impact is determined by a straightened shock-compression curve based on the expression:

\[ a_{sh} = \frac{\epsilon_1 - \epsilon_2}{\eta_1 - \eta_2} \]

where \( \epsilon_1, \epsilon_2 \) – porosity of the sand compacted at acceleration of oscillations \( \eta_1 \) and \( \eta_2 \).

The effect of static loading of soils on their porosity, and through its critical value for the liquefaction process is determined from the equation:

\[ \epsilon_k = \epsilon_0 - a_{sh} [\sigma(\epsilon_0) - \sigma_p] \]

where \( \epsilon_0 \) – initial porosity coefficient; \( \sigma(\epsilon_0) \) – static voltages at \( \epsilon_0 \) and \( \eta \); \( \epsilon_k \) – the final porosity coefficient, at operating stresses in the soil \( \sigma_p \) at the time of acceleration of oscillations \( \eta \).

The porosity of sand at any given acceleration of oscillations \( \eta \) is determined according to the dependence (13) from the expression:

\[ \epsilon = b - a_{sh} \eta, \]

where \( b \) – initial value of porosity coefficient.

Static load reduces the probability of soil structure destruction and improves its compaction under dynamic influences [11], [15]. During the vibration in the watered soils volumetric deformations are accumulated, causing vibration creep of incoherent soils. Accounting for this phenomenon is carried out using the correction factor \( \propto \) :

\[ \propto = 1 - e^{-\gamma_i t}, \]

where \( \gamma_i \) – vibration creep parameter, 1/minute; \( t \) – time, minute.

Given the expression (17), equation (14) takes the form:

\[ \epsilon(t) = \epsilon_0 - a_{sh} [\sigma(\epsilon_0) - \sigma_p] \propto 1 - e^{-\gamma_i t} \]

where \( \sigma(t) \) – porosity at the time \( t \).

The value of \( \sigma(t) \), determined depending on the values of the static strength of the sand, dynamic vibration loads (through the value \( a_{sh} \)) and taking into account the vibration creep, allows you to find the critical gradient of the pressure at which the soil is liquefied and flows (1).

5. Conclusion

In underground structures, in result of removal of soil particles through leaks, there is a decompression of the soil behind the lining, a change in its filtration coefficient, granulometric composition, absolute and relative porosity, which ultimately leads to catastrophic destruction of the lining. This is the fundamental difference between the process of removal of soil into the underground structure from the cases of violation of the foundations of structures recorded in the practice of construction or underpinning works [16,17]. Therefore, it is necessary to provide a proper monitoring system [18-20] and make it possible to avoid the harmful effects of soil removal due to the lining of the underground structure by taking into account the specifics of their interaction with the adjacent soil or rock mass and finding effective means of preventing them.

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