Technological Soil Mechanics in Underground Construction

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Abstract. The article is devoted to the application of the technological soil mechanics principles in the design and construction of underground structures, also in problematic soils – loose water-saturated sands. The definition of technological soil mechanics is given. The relevance of the research topic is justified. A quantitative assessment of the stress strain behavior (SSB) of the soil mass containing the support system of deep pits, depending on the technology and sequence of work during underground construction, was made. The possibility of the SSB of ground mass managing during underground construction in order to select the most economical options for design and technological solutions is proved. Recommendations for SSB management of underground parts of buildings and structures, as well as the surrounding soil mass, based on the technological soil mechanics application are formulated.

1. Introduction
Technological soil mechanics is a set of provisions that justify the need to take into account the technology and sequence of work in geotechnical calculations of the soil mass-underground parts of structures interaction.

Construction and design of underground structures, also in problematic soils – loose water-saturated sands – is not fully provided with regulatory documentation. Requires numerical calculations of SSB for soil mass, underground structures and protective measures for the surrounding built up area and field experiments (observations of ground mass displacements, containing underground facilities, building foundations and structures in their area of influence, including the period of the protective measures installation).

Changing the excavation sequence and the technology of works in underground construction, leads to a change in magnitude and sometimes sign of the forces in underground structures, and also displacement values of soil bases. The latter also occurs when changing the technology of protective measures installation for buildings in the zone of deep pits impact.

Failure to take into account the technology and sequence of work on the construction of underground structures and protective measures during geotechnical calculations of the SSB of soil mass can lead not only to the loss of operational suitability of underground structures and surrounding buildings, but also to their destruction, especially in problem soils – loose water-saturated sands.
Therefore, research in the field of technological soil mechanics development and its application in underground construction, aimed at ensuring the structural safety of objects with an underground part, is relevant.

The use of technological soil mechanics makes it possible to manage the SSB of soil mass containing underground parts of buildings and structures, in order to ensure the safety of underground construction and select the most economical design and technological solutions for objects with an underground part.

2. The study of the issue on the application of technological soil mechanics in underground construction

Current state of research in Russia and abroad on the management of the stress-strain behavior of the soil mass, containing underground parts of buildings and structures, in order to ensure their structural safety, presented by the works of Russian [1,2,3,4,5,6,7,8,9 etc.] and foreign scientists [10,11,12,13 etc.]. Their research has shown that changing the sequence of work during underground construction leads to a change in the magnitude, and sometimes the sign of forces in the underground structures, and also significantly affects the displacement of the soil mass.

To ensure the structural stability of underground objects, it is necessary to take into account the provisions of technological soil mechanics, the founder of which is RAACS academician V. A. Ilyichev, who first used this term when studying the SSB of the high-power turbine units bases [1] (1m. 200 thousand kW). The term reflects the interaction of structures and soil mass.

When managing the stress-strain behavior of underground parts of buildings and structures, as well as the surrounding soil mass, based on the application of technological soil mechanics, it is necessary to take into account technological settlements caused by the work of construction equipment on the site, changes in the properties of certain soil types of (unstructuring of weak clay soils, deconsolidation of sands, etc.), violation of technological regulations. The method of forecasting some types of technological settlements is described in the works of Mangushev R. A. and Nikiforova N. S. [14], Shulyatev O. A. et al. [15,16], Razvodovsky D. E. and Chepurnova A. A. [17], Ilyichev V. A. et al. [18], Nikiforova N. S. et al. [19-21].

Based on the analysis of international and Russian experience in the study of stress-strain state of the soil mass, underground structures (slabs of large dimensions, deep-level supports) and underground objects (tunnels, deep pit support), depending on the technology and work sequence, set the direction of research and the methods of their conduct, including numerical modeling, analytical studies and field observations of settlements at underground construction sites.

3. Application of the technological soil mechanics principles for construction in problematic soils

On the example of Moscow construction objects, numerical modeling has been used to quantify the SSB of a soil mass, including one composed of problematic soils (loose water-saturated sands), containing underground structures, foundations of existing buildings (settlements, relative difference in settlement, horizontal displacements of deep pit support structure), depending on the technology and work sequence during underground construction, technology of protective measures installation for the existing buildings, aimed at developing the provisions of technological soil mechanics.

Loose, also water-saturated sands, are considered as problematic soils. The presence of a large thickness of loose water-saturated sands that can be compacted under various types of impacts (dewatering, dynamic effects, etc.) can cause difference in settlement of buildings and structures located on them, as well as underground objects. Violation of the technology of work during underground construction in these soils can also cause the removal of water-saturated soil into the pit or well and, accordingly, surface settlement. In addition, suffusion processes that can occur in loose water-saturated sands contribute to the above-mentioned negative processes.

When designing a multi-functional high-rise complex of three 52-storey towers with four-level underground parking on 11-13 Proezd Serebryakova street in Moscow, which was based on loose water-saturated sands, four technological solutions for excavation support system was under
consideration: anchors, struts, their combination and the installation of a floor slab in the pit along the building in the impact zone.

Shadings of vertical displacements of the soil mass for four variants of technological solutions and the sequence of work during its excavation are shown in figure 1.

The building at 3 Nansen street was located in the zone of construction impact. The table 1 shows values of additional deformations of the soil under this building caused by the construction of a high-rise complex and the horizontal displacement of the pit support.

For all construction solutions, the additional deformations from the pit excavation did not exceed the limit values, but they reached them for options № 1,2,4. If we take into account that the calculations were performed without considering the technological part of settlement, we can conclude that option № 3 is preferable.

![Figure 1](image_url)

*Figure 1. Shadings of vertical displacements: a) solution №1; b) solution №2; c) solution № 3; d) solution №4.*

| solution № | $S_{ad}^{max}$, cm | $(\Delta S/L)$ | $U_{h}^{max}$, mm |
|------------|---------------------|----------------|-------------------|
| 1          | 3,0                 | 0,001          | 63                |
| 2          | 3,0                 | 0,0009         | 76                |
| 3          | 2,5                 | 0,0003         | 53                |
| 4          | 3,0                 | 0,0001         | 39                |

As a result of calculations for a number of Moscow construction objects, it was proved that:

- when excavating a pit in loose water-saturated sands in the presence of adjacent buildings, it is advisable to build using the "top-down" or "semi-top-down" method. The use of the
construction method with struts in loose sands can lead to excessive settlements of existing buildings;

- it is preferable to transform loose sands (for example, stabilization) by some method to prevent their removal into the cavity during the construction of a pit support (diaphragm wall, bored piles) or compaction due to dynamic impacts from operating machinery. At the same time, it should be taken into account that the injection of quick-setting cement mortar into loose water-saturated sands and their subsequent incrustation can lead to piping, which causes additional settlement of the existing buildings.

4. **Suggestions for recommendations on SSB management of underground structures and soil mass**

Based on the analysis of Russian and foreign research, and a series of numerical calculations, suggestions were formulated for recommendations on SSB management of underground parts of buildings and structures, as well as the surrounding soil mass, based on the application of technological soil mechanics. Proposals include the following:

1. In determining the SSB for foundation slabs of large sizes and thicknesses with the technological sequence of concreting, it is recommended to use a method of determining contact stresses at the base of the slabs, designed by Ilichev V. A. [1]. This method is based on the solution of beam on elastic and consolidated base.

2. The SSB of tunnel lining is managed based on geotechnical calculations of various technological sequence variants for tunnel cross-section cutting and the order of tunnel (galleries, if there are several of them) sinking.

3. Management of soil mass displacement (vertical and horizontal) should be performed on the basis of following geotechnical calculations (using the methods described in the works):
   - calculations based on several variants of the technological sequence of deep pits support system installation (to minimize displacement "top-down" method should be used);
   - calculations justifying controlled jet grouting behind the support structure and under the bottom of pits ([22]);
   - calculations justifying the controlled injection of cement mortar outside the tunnel lining ([8]);
   - calculations justifying the volume of cement mortar injected under foundations of existing buildings to ensure the limit values of additional deformations ([6]);
   - calculations that justify the amount of force in jacks installed on struts to impact the diaphragm wall ([9]);
   - calculations that take into account technological settlement ([14,20,21]).

5. **Conclusion**

1. On the example of Moscow construction objects, a quantitative stress-strain behavior assessment of the soil mass was made, including problematic soils (loose water-saturated sands), containing parts of underground structures, foundations of existing buildings (depending on the technology and sequence of work during underground construction, the technology of protective measures installation). Quantitative assessment formed the basis for the development of technological soil mechanics provisions.

2. The possibility of managing the stress-strain behavior of soil mass containing underground structures was proved by using the provisions of technological soil mechanics, in order to ensure the safety and efficiency of underground construction.

3. Scientific-based suggestions were made for recommendations on how to consider the sequence and technology of work in the design and construction of underground structures, also in problematic soils – loose water-saturated sands.
6. References

[1] Ilyichev V A 2007 Sovremennaya mehanika – prakticheskomu stroitel'ству Russian geotectnics – step into the 21st century (Moscow) pp 80-104
[2] Kolybin I V and Fursov A A 2000 Raschet podzemnyh sooruzheniy s uchetom tekhnologii ih vozvedeniya Proc. of Research Institute of Bases and Underground Structures (Moscow) pp 1-8
[3] Ilyichev V A 2017 Tekhnologicheskaya mehanika gruntov Optimal'noe i estestvennoe proektirovanie, dinamika gruntov, i peredacha kolebanii cherez grunt, sejsmostojkost’ svajnyh fundamentov Russian Conf. Deep foundations and geotechnical problems (Perm)
[4] Ilyichev V A, Nikiforova N S, Konnov A V 2017 Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Tekhnologiya Tekstil’noi Promyshlennosti 2 245-249
[5] Ilyichev V A, Nikiforova N S, Gotman Yu A, Trofimov E Yu 2015 ZHilishchnoe stroitel’stvo 6 11-15
[6] Simutin A N 2015 Metodiki rascheta parametrov kompensacionnogo magnetaniya dlja upravljeniya deformациyami osnovaniy zdaniy i sooruzheniy (Moscow)
[7] Ilyichev V A and Mangushev R A 2016 Geotechnical Engineer’s Handbook. Footings, foundations, underground structures (Moscow: ASV)
[8] Ilyichev V A, Nikiforova N S, Tupikov M M 2013 Building deformations, induced by shallow service tunnel construction and predictive measures for reducing of its influence 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering. Challenges and innovations in geotechnics (Paris) pp 1723-1726
[9] Ilyichev V A, Nikiforova N S, Gotman Yu A, Tupikov M M, Trofimov E Yu 2013 ZHilishchnoe stroitel’stvo 6 25-27
[10] Anthony Deane, Jeno Rulff June 1992 World Tunneling Magazine 242-246
[11] Bowers K H, Hiller D M, New B M 1996 Ground movements over three years at the Heathrow Express Trial Tunnel Geotechnical aspects of underground construction in soft ground (Balkema)
[12] 1996 Safety of New Austrian Tunneling Method (NATM) Tunnels (London: HSE)
[13] Mair R J 2008 Ge’otechnique 9 695–736 doi: 10.1680/geot.2008.58.9.695
[14] Mangushev R A and Nikiforova N S 2017 Tekhnologicheskie osadki v zone vliyaniya podzemnogo stroitel’stva (Moscow: ASV)
[15] Shulyatev O A, Mozgacheva O A, Minakov D K and Solovyov D Y 2016 Acad. Arhit. i Stroit. 4 129–40
[16] Shulyatev O A, Mozgacheva O A, Pospekhov V S 2017 Osvoenie podzemnogo prostranstva gorodov (Moscow: ASV)
[17] Razvodovskii, D.E. Chepurnova A A 2016 Promyshlennoe i grazhdansko Stroit. 10 64–72
[18] Ilyichev V A, Mangushev R A, Nikiforova N S, Konnov A V 2017 Byulleten’ Stroit. tekhniki 6 68-69
[19] Nikiforova N, Konnov A, Zakirova A 2018 IOP Conf. Ser.: Mater. Sci. Eng. 463 042012
[20] Nikiforova N S and Konnov A V 2020 Protection of existing structures during underground development including problematic soils The 2nd Russia - USA Geo-engineering Symp. “Improvement of Design Codes” ed J-L Briaud and V A Ilyichev (Moscow, St. Petersburg) pp 201–12
[21] Nadezhda Nikiforova and Artem Konnov 2018 IOP Conf.Ser.: Mater. Sci. Eng. 365 042028
[22] Ilyichev V A, Gotman Yu A 2011 Osnovaniya, fundamenty i mekanika gruntov 4 24-31

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