Modeling the stability of horizontal generations worked in parallel to the front of a uniform slope

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Abstract. Improvement of modern urban infrastructure, expansion of transport networks, creation of innovative engineering communications – as well as other circumstances stimulate the development of underground construction, both in our country and abroad. Like any underground structure, it should have the ability not to collapse when exposed to external loads. For the successful operation of such structures throughout their entire service life, it is necessary to constantly assess the influence degree of all factors’ totality, one way or another, affect its strength. The task, the purpose of which is to conduct the experimental studies on models made of equivalent materials to assess the geometric parameters’ influence of the “slope – underground working space” system on the stability of the latter, has been set. Geometric parameters mean the shape of the underground working space cross-section and its position in the soil massif: the shape of the underground working space cross-section is round and semi-elliptical; the underground working spaces’ bottom is at the level of the slope bottom, the underground working space position is determined by the shortest distance from the transition point of the bottom to the slope to the vertical axis of the cross-section symmetry. The criterion for long-term stability is a criterion, the qualitative feature of which is the absence of inelastic (plastic) deformation zones on the development contours, and the quantitative indicator is the value of the reduced pressure of connectivity $\sigma_{\text{con}}$. As a result of model experiments, safe distances $d$ were determined, on which underground working spaces should be located in the near-slope area so that the stability of the “slope - underground working space” system is ensured. It turned out that these distances for underground working spaces of both circular and semi-elliptical cross-section are practically the same, that is, the underground working spaces of such a cross-section, all other sections being equal, were equally stable. Practical coincidence of the model experiments’ results and numerical finite element analysis, calculations, allows us to speak about the experimental data reliability.

Introduction

The underground space development, associated with the transport infrastructure expansion in large cities due to population growth and an increase in the road traffic volume, is proceeding at a rapid pace, which ensures an increase in the underground construction volume.

The issues related to the underground space development are quite relevant, as evidenced by the large number of scientific publications on this topic and the growth of the planned volume of construction work. For example, in the city of Volgograd, due to the peculiarities of the relief, the tram
lines are partially underground. Now the length of the underground section is more than 7 kilometers, and in the near future it will be extended by another 4 km.

![Figure 1. Underground space of high-speed tram stations in the city of Volgograd](image)

The cost of underground construction is quite high, which is associated with the need to implement a number of measures to ensure the stability of the underground complex and aboveground structures. It is possible to reduce the corresponding costs using the special techniques and calculation methods that allow determining the safe parameters of underground working spaces and ensuring the safe operation of facilities in the future. The stability of underground structures (underground working spaces) depends on a number of factors: geometric dimensions, cross-sectional shape, features of the geological structure and relief, external loads, physical and mechanical properties of the enclosing soil, and much more.

One of the important tasks in underground construction, in particular, in the construction of transport tunnels in mountainous terrain, is to determine the position of the underground working space in the slope region, which would guarantee the stability of the “slope – underground working space” system without taking any additional measures to strengthen it.

In this regard, we carried out the experiments aimed at determining such geometrical dimensions and such a position of unsecured horizontal underground working spaces of a circular and semi-ellipsoidal cross-section, in which the plastic deformation areas or destruction zones do not appear on their contour of underground working spaces. We call such geometrical parameters safe and consider the production itself stable when these parameters are maintained.

During the experimental studies, the slope models were formed in an experimental tray with the following dimensions of 1.0 × 1.79 × 0.105 m, the side faces of which were made of 8 mm thick plexiglass (see Figure 1a).

In the slope models, the voids were created (using the laid-out templates), simulating underground working spaces with a cross-sectional shape in the form of a circle and half an ellipse. The position of the underground working spaces was determined by the distance $L$, measured by the shortest distance from the slope transition line to its base to the vertical axis of the underground working space symmetry.

When forming the models from an equivalent material, the value $L=0,15H; 0,2H; 0,25H; 0,3H$, and the slope model angle $\beta=60^\circ$. The base width of the semi-elliptical underground working space is taken equal to the diameter of the circular underground working space $d=0,1H$. The geometric parameters, dimensions of the model are given in fractions of its height $H=0,6$ m. (see Figures 2c, 2d).
A sand-oil mixture was used as an equivalent material from which the slope models were formed, the shear characteristics of which in the unconsolidated and compacted state were established by testing at consolidated shear in the GGP-30 box shear apparatus (Figure 3a). The tests were carried out in the soil mechanics laboratory LLC “Radian”.

Shear diagrams are shown in Figures 3 b, c, the numerical values of physical and mechanical properties - respectively in Tables 1 and 2.
Figure 3. Box shear apparatus GGP-30 (a) and shear diagrams of unconsolidated and compacted equivalent material (b, c)

Table 1. Physical and mechanical properties of an equivalent material in consolidated state

| P, [MPa] | \(\tau, [\text{MPa}]\) | \(\text{tg } \varphi\) | \(\varphi\) | \(\text{Sh}, [\text{kPa}]\) |
|---------|----------------|--------|------|-----------|
|         | experiment | calculation |        |           |
| 0.1     | 0.06       | 0.06   | 0.55 | 28°49'   |
| 0.2     | 0.115      | 0.115  |       |           |
| 0.3     | 0.17       | 0.17   |       |           |

Table 2. Physical and mechanical properties of an equivalent material in unconsolidated state

| P, [MPa] | \(\tau, [\text{MPa}]\) | \(\text{tg } \varphi\) | \(\varphi\) | \(\text{Sh}, [\text{kPa}]\) |
|---------|----------------|--------|------|-----------|
|         | experiment | calculation |        |           |
| 0.1     | 0.06       | 0.06   | 0.575 | 29°54'   |
| 0.2     | 0.118      | 0.118  |       |           |
| 0.3     | 0.175      | 0.175  |       |           |

The average value of the equivalent material bulk density of the models is determined to be \(\gamma=17.2\text{kN/m}^3\); and the value of its lateral pressure coefficient, found on the basis of the method of K. Terzaghi [1-3] - \(\xi_0=0.4\).

Slope models were generated as follows. On the front wall of the box, the contour of the future model was outlined with colored chalk, taking into account the geometric dimensions and parameters adopted during the modeling. At the first stage, a layer of equivalent material was laid to a height from the bottom of the chute to the lower boundaries of the underground working space templates fixed on the walls of the experimental chute. Subsequent layers, approximately 10 cm thick, were laid alternately with a time delay of about 30 minutes after the previous layer completion of the equivalent material for natural compaction. A tray filled in this manner was left for three hours to allow gravitational compaction of the equivalent material. After this time, a careful extraction of soil from a part of the chute was carried out (unloading, underground working space off the slope), and a slope model was formed. After the formation of the model, it was photographed, and it was again left for three hours to redistribute the stresses in connection with the model “unloading”. After that, a careful extraction of the box-template was carried out, photographing of the model, violations’ fixation of its integrity and the state of the underground working space imitation. Photos of the models taken before and after removing the box are shown in Figures 4 and 5.
Figure 4. Photographs of a slope model made of equivalent material, undermined by a round horizontal underground working space, before and after removing the template box at the distances L=0.15H (a; b), 0.2H (c; d), 0.25H (e; f), 0.3H (g; h).

The results show that for $L \geq 0.3H$ the stability of underground working spaces with a round and semi-elliptical cross-sectional shape is ensured with almost the same values $d$ provided that the physical and mechanical properties of the equivalent material of the model and the transverse dimensions of the simulation underground working spaces are the same.

In addition to physical modeling of the stability loss process of the “slope - underground working space” system, computer modeling of this process was performed. For this, the computer program “Stability. Stress state” [4], developed with the participation of one of the authors of this work, was used. To calculate stresses, the program formalized the finite element method (FEM). The program gives a possibility to use the stability criterion [5; 6], the qualitative feature of which is the absence of inelastic deformations areas on the development contour, and the quantitative indicator is the value of the reduced pressure of connectivity $\sigma_{con}=C(\gamma H t g\varphi)^1$, where: $C$, $\gamma$, $\varphi$ – are respectively specific adhesion, angle of internal friction and volumetric weight of equivalent material; $H$ – is the height of the slope model. To find the shear ranges (APD), the program uses the Coulomb strength condition [7] in the form presented by G. Cacko [8].
Figures 5 and 6 graphically represent the computer simulation results. It turned out that the values $L$, calculated using a computer program [4] differ by no more than 7-15% from the similar distances obtained experimentally.

This circumstance gives an opportunity to conclude that it is possible to use the program [4] to solve similar problems.

Based on this premise, the buckling process computer simulation of single horizontal underground working spaces with a circular cross-section of variable diameter was performed $d=(0,05; 0,15; 0,2; 0,25; 0,3)h$, which are alternately located at the distances $L=h$; $L=h+((2h/tg\beta–h)/2)$; $L=2h/tg\beta$ from A points of the slope transition to the bottom (see the design diagram in Figure 7).
The slope angle takes three values $\beta = 25^\circ$, $45^\circ$, $60^\circ$, and the value of the reduced pressure of connectivity in the calculation is assigned as six values $\sigma_{\text{con}} = 0,1; 0,5; 1; 2; 2,75; 3,5$. All calculations are performed with the value of the lateral pressure coefficient $\xi_0 = 0,75$, which corresponds to the average value for clayey soils [9-11].

All the calculations, as before, were performed using the computer program “Stability. Stress state” [4] and the FEA computer program [12], which was also developed with the participation of one of the authors of this article.

The view of the FEM design scheme with the main geometric dimensions and boundary conditions is shown in Fig. 7.

As a result of the calculations performed, for all possible combinations of numerical values of variable design parameters, the “safe” values of the soil internal friction angles of the enclosing mass $\phi_s$, which ensure the presence of a qualitative trait, have been defined.

Based on the calculation results analysis, the graphical dependencies of the form $\phi_s = f(\sigma_{\text{con}})$, some of which are shown in Fig. 8, have been built. It was found that all the curves obtained can be approximated by the expression:

$$\phi_s = a \sigma_{\text{con}}^b,$$

where: $a$ and $b$ – are the real coefficients, moreover, the coefficient $a$ has the dimension [deg], and the coefficient $b$ – is a dimensionless quantity.
Figure 8. Graphical dependencies view $\phi_s = f(\sigma_{con})$ at different values of the underground working space diameter $\beta=25^\circ$ (a); $\beta=45^\circ$ (b); $\beta=60^\circ$ (c) at a distance from the center of the underground working space to the point A $L=h$ (a); $L=h+((2h/tg\beta-h)/2)$ (b) and $L=2h/tg\beta$ (c) respectively.

As a result of the numerical values’ analysis of the coefficients included in the expression (4), the graphs were built to determine their numerical values, which are shown in Figures 9; 10. The curves’ analysis shown in Fig. 9 shows that the change in the relative (in fractions $h$) underground working space diameter from 0.05 to 0.3 for all the considered distances from the center of the underground working space to the point A, entails a change in the value of the coefficient $b$ for 7-18%.

Figure 9. Graphs for determining the numerical value of the coefficient $a$ depending on the relative underground working space diameter at $L=h$ (a); $L=h+((2h/tg\beta-h)/2)$ (b) and $L=2h/tg\beta$ (c).

Figure 10. Graphs for determining the numerical value of the coefficient $b$ depending on the relative underground working space diameter at $L=h$ (a); $L=h+((2h/tg\beta-h)/2)$ (b) and $L=2h/tg\beta$ (c).

As a result of the additional calculations, it was established: if we take the value of the coefficient $b$ constant and equal $b=-0.62$, then the numerical values of the quantity $\phi_s$, obtained on the basis of formula (4) and the graphs shown in Fig. 9 and 10 will differ from the corresponding values $\phi_s$, calculated by the formula

$$\phi_s = a\sigma_{con}^{-0.62}$$  

using the graphs shown in Fig. 8, no more than 10%, moreover, this difference goes into the stability margin.

Summary
1. The stability of a horizontal underground working space depends on the geometrical parameters of the slope and the underground working space, its location, physical and mechanical properties of the
constituent soil. The closer the underground working space is located to the base of the slope, the more intensively, all other things being equal, the process of destruction of its contour proceeds.

2. Graphical dependencies and analytical expressions, which together represent an engineering method for a preliminary assessment of the stability of a horizontal underground working space of a circular cross-section worked out in a homogeneous soil slope at the level of its bottom, have been obtained.

3. Verification calculations showed that the numerical values of the quantity $\varphi$, friction obtained on the basis of the proposed engineering method differ by no more than 10.2% from the results obtained by direct use of the computer programs [4; 12], and the error goes into the stability margin.

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