Numerical and physical modeling of the stability of the workings developing the slope

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Abstract. Enhancement of modern urban infrastructure, expansion of transport networks, creation of innovative engineering communications as well as plenty more factors stimulate the development of underground construction both in our country and throughout the world. Like any structure, an underground construction must be capable to perceive external loads without collapsing. For the successful operation of such structures throughout all term of their service, it is necessary to evaluate regularly the impact degree of all factors that one way or the other affect the construction durability. It was therefore decided to study by means of a model experiment, how the geometric parameters of the slope and underground workings’ system affect the stability of the latter. We'll assume the cross-sectional shape of the workings and their position relative to the basis of a model from homogeneous ground massif as the geometric parameters. In this paper we examine the stability of the models of horizontal underground workings with round and semi-elliptical shape worked in an isotropic soil slope, at various distances from the point of transition of the sole into a slope. As a measure of long-term stability we chose the criterion (Bogomolov A.N., Bogomolova O.A., 2010) where a qualitative feature is the absence of zones of inelastic (plastic) deformations on the contours of the workings as well as zones manifesting the processes of loosening or breed fragmentation.

The value of the reduced pressure of coherency $\sigma_c$ is used as a quantitative indicator. The paper presents the results of numerical processing of model experiments studying the fracture processes both of the ground slope weakened by the workings and the workings themselves. In the course of the model experiments, we defined the distances $L$, measured from the base of the slope to the center of the workings with circular and semi-elliptical cross-sectional shape, under which the contour of the workings was stable. It is established that the stability of the round and semi-elliptical shaped workings can be provided practically at the same values of $L$ on condition that the physical and mechanical properties of the equivalent material of the model, its geometric parameters and the transverse dimensions of the imitation workings are practically identical. The coincidence of the results of model experiments and calculations performed with the help of a computer program makes it possible to speak about their reliability.

1. Introduction

The exploration of the underground space associated with the expansion of the transport infrastructure of large cities due to the population growth and the increased automobile traffic, runs at a rapid pace, which contributes to the development of the underground construction. The issues related to the exploration of the underground space are topical enough, which is evidenced by a large number of the relevant scientific publications and the planned construction work. For example, in the city of...
Volgograd, the tram tracks are partially laid underground due to the topography peculiarity. Now the length of the underground section equals to 7.1 km. In future they plan to expand further the existing network.

Figure 1. Photographs of the underground tram stations (a); the scheme of the existing and the projected areas of the speed (underground) tram (b)

The cost of underground construction is quite high due to the necessity of carrying out a number of measures aimed to protect both the aboveground and the underground structures.

The related costs can be reduced thanks to adopting the special techniques and methods of calculation that will allow to determine the safe parameters of the underground workings as well as to ensure adequately the safe operation of the facilities in the future. The stability of the underground structures (workings) depends on a number of factors, such as their geometric dimensions (characteristics) and their form, the topography peculiarity, the external loads and the physical and mechanical properties of the enclosing soil. This regard, we performed some model experiments, which were aimed at the definition of such geometric dimensions and such a position of the floating horizontal underground workings with the different cross-sectional shape formed in the model of isotropic soil escarpment, that could prevent the appearance of areas of plastic deformation in their contour, i.e. there could occur no zones of destruction. Such geometric parameters we can call safe, and the excavation itself can be considered stable.

This article [1] presents the materials, allowing to compare the stability of excavations of the circular and semi-elliptical cross-sectional shape. Herewith it was found that the regions of plastic deformation on the contours of the workings with the circular and the semi-elliptical cross-sectional shape are practically identical, under the condition of the equality of the numerical values of their geometrical parameters, the physical and mechanical properties of the accommodating equivalent
material and the positions of the simulation workings in the body of the model. All the calculations, given here, are performed with the help of a computer program "Stability. Stress state" [2], developed by a research team of the Volgograd State University of Architecture and Civil Engineering (Russia). In this program they implemented, among the others, a model of the linearly deformable elastic media. Thus we formalized the finite element method (FEM) to calculate the stresses at the points of the escarpment area and on the contour of the workings. As a stability measure we used the criterion [3], which qualitative feature is the lack of the inelastic deformations regions on the contours of the workings, besides we applied the value of the reduced pressure of connectedness, as the quantitative indicator \[ \sigma_e = c \cdot (\gamma \cdot H \cdot \tan \varphi)^{-1} \] , where one can distinguish accordingly:

\( c \) as the specific cohesion, \( \varphi \) as the angle of the internal friction, \( \gamma \) as the volumetric weight of the equivalent material and \( H \) as the height of the model slope. The value of the coefficient of lateral pressure of the equivalent material was determined by the method of K.Terzaghi. There was performed an entire range of model experiments, presented below, to confirm the possibility of applying the above mentioned computer program to carry out the corresponding numerical studies as well as the determination of the adequacy of the data provided in this paper [1].

2. Materials and methods

The slope models were formed in the experimental tray measuring 1.0 m x 1.79 m x 0.105 m and having the side faces made of Plexiglas with a thickness of 8 mm (see figure 2a).

In the slope models we thus created a series of workings (with the help of the laid templates) having the cross-sectional shape in the form of a circle or a half of an ellipse. The position of the workings was determined by the value of the distance \( L \), i.e. from the bottom of the curve of the slope to the center of the workings. In this connection: \( L = 0.15 \, H; \, 0.2 \, H; \, 0.25 \, H; \, 0.3 \, H \). The angle of steepness of the model slope was \( \beta = 60^\circ \). The width of the basis of the semi-elliptic workings was equal to the diameter \( d = 0.1 \, H \) of the circular workings. The geometric parameters of the slope model and all its dimensions are given in fractions of the model height \( H = 50 \, cm \) (see Fig. 2b, 2c).

![Figure 2](image-url)
data tables No 1 and No 2. The strength properties of the material were established by testing it with a consolidated shift in the GGP-30 device at the laboratory of the soil engineering of Radian LLC. These test results are shown in data tables 1, 2 and Fig. 3.

| P, MPa | \( \tau \), MPa | \( \varphi \), MPa | \( C \), kPa |
|------|----------------|----------------|----------|
| 0.1  | 0.06           | 0.06           |          |
| 0.2  | 0.115          | 0.115          | 0.55     |
| 0.3  | 0.17           | 0.17           |          |

| P, MPa | \( \tau \), MPa | \( \varphi \), MPa | \( C \), kPa |
|------|----------------|----------------|----------|
| 0.1  | 0.06           | 0.06           |          |
| 0.2  | 0.118          | 0.118          | 0.575    |
| 0.3  | 0.175          | 0.175          | 2.5      |

**Table 1.**

**Table 2.**

**Figure 3.** The shift diagrams of the non-compacted and compacted equivalent material (a, b) and the shearing device GGP-30 (c)

The average value of the volumetric weight of the model equivalent material was defined as \( \gamma = 17.2 \) kH/m\(^3\); while the coefficient of lateral pressure, found on the basis of K. Terzaghi method [5-7], was equal, as noted above, to \( \zeta_o = 0.4 \). The slope models were formed in the following way. The outline of the future model was delineated with the colored chalk on the front wall of the box, according to the distances and sizes, adopted in the simulation. At first stage a layer of the equivalent material was placed to fill up the height from the bottom of the tray to the bottom borders of the workings' templates, fixed on the sides of the experimental tray. The next layers, with a thickness approximately equal to 10 cm, were fitting with a pause of about 30 minutes after the end of covering of the previous
layer. The tray, filled in this way, was left undisturbed for three hours to ensure the establishment of the stress field generated by the force of gravity. At the end of this time, the soil was to be carefully removed from the part of the tray (unloading, working off the slope) to form a slope model. After being properly formed the model was photographed and then left again undisturbed for three hours for the redistribution of stresses due to the "unloading" of the model. Thereafter the box-template was to be carefully removed and the model was to be photographed for determining the violations of its integrity and studying the state of the imitation workings. The photos of the models before and after the box’s removal are given in Fig. 4.

**Figure 4.** The photos of the model of a slope from an equivalent material, worked out by the round and semi-elliptical horizontal excavation, before and after the extraction of the template box at the distances of $L = 0.15\ H$ (a; b; i; j), $0.2\ H$ (c; d; k; l), $0.25\ H$ (e; f; m; n), $0.3\ H$ (g; h; o; p)
3. Results

It is established that at $L \geq 0.3 \, H$, the stability of the round and semi-elliptical shaped workings is provided practically at the same values of $L$ on condition that the physical and mechanical properties of the equivalent material of the model, its geometric parameters and the transverse dimensions of the imitation workings are practically identical. Calculating of the computer slope models by means of the program [2], performed in compliance with all the conditions of the physical experiment, showed that the workings at $L \geq 0.3 \, H$ remain stable.

![Figure 5](image)

Figure 5. The pictures of the regions with the plastic deformations of the circular and semi-elliptical shaped workings, at the distances of $L = 0.15 \, H$ (a; e), $L = 0.20 \, H$ (b; f), $L = 0.25 \, H$ (c; g), $L = 0.3 \, H$ (d; h)

4. Discussions

The results of the research underlying the present article were reported and published in the proceedings of the International scientific and practical conferences such as «Topical areas of fundamental and applied research XIV» (North Charleston, USA. 2017), «Integration of modern scientific research into the development of society» (Kemerovo, Russian Federation. 2017), «Actual problems of science of the XXI century» (Moscow, Russian Federation. 2017), «World science: problems and innovations» (Penza, Russian Federation. 2018).

At the discussion of the article on the merits within the seminar of the Department of «Hydraulic Engineering and Earth Structures» it was noted that in the course of the performed studies there were obtained new data on the development of the plastic deformation areas on a contour of the underground workings located in a soil massif near a slope. The adequate conformity of the qualitative and quantitative results of the physical modeling with the results of the numerical analysis allows it to speak about their reliability.
The practical value of the obtained data consists in giving the possibility to predict the stability of the underground workings, depending on their position in the host soil massif as well as the stability of the developed soil slope. It was noted the need to continue the researches aimed at studying the stability of the slopes, developed by the workings of other configurations as well as the stability of the underground workings.

As a result of the discussion, the material of the research was recommended for the publication in the proceedings of the XXI International scientific conference «Construction as formation of living environment».

5. Conclusions
Based on the comparison of the results of numerical and physical experiments, and the data given in the paper [1], we can draw the following conclusions:

1. The results of numerical and physical (model) studies, aimed at determining the safe values of distances $L$, show that the values $L$ are almost identical for the workings with a circular and a semi-elliptical cross-sectional shape, provided that the geometric parameters of the slope models are the same and the physical and mechanical properties of the applied equivalent material are equal. The area of plastic deformation on the contour of the workings is practically absent at $L = 0.3\ H$ for the workings of both cross-sectional shapes, and the model of the slope as well as the workings themselves remain stable.

2. The workings having a circular and a semi-elliptical cross-sectional shapes can be regarded as equally stable under the conditions of the performed experiment.

3. The coincidence of the results of model experiments and calculations performed with the help of a computer program makes it possible to speak about their credibility. It allows us to recommend a computer program [2] for the numerical processing of the research results on the models from the above-mentioned equivalent material, provided that the underground workings will have a different configuration.

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