Possible methods analysis and optimization of the landslide slope stabilization in the reconstruction area of the escalator gallery on the Moscow River shore

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Abstract. This work solves the current task of construction on the landslide slope of the escalator gallery. The purpose of this work is to analyze and optimize various methods of stabilization of the soil mass and to identify the optimal solution for its strengthening. As a result of the calculations carried out, the most suitable option for strengthening the slope was found, which simultaneously had low material consumption and provided sufficient stability of the slope.

1. Introduction

In 1959, a metro station was opened in Moscow, which was a unique object, as it was located on a bridge above the river. In the same year, an escalator gallery opened near the station, designed for quick and convenient access to metro passengers. The gallery was 3 escalators 90 meters long each, covered on top by a stepped canopy. During operation, due to landslides and rock displacement, the walls of the gallery were covered with cracks, and it gradually came into an emergency condition. The gallery was not repaired for a long time due to lack of profitability and in October 1983 due to the end of the safe operation period escalators suspended work for passengers. As of 1988, even their preventive launches were discontinued. All three escalators were later dismantled and the upper lobby demolished in 2001.

According to the given data of engineering surveys and monitoring, as well as research and analysis of stock materials, the landslide slope on the site of the Escalator Gallery following SP 420.1325800.2018 is characterized as:

- the depth of capture - very deep (depth of rock grip by landslide deformations exceeds 20 m);
- By volume - very large (total volume exceeds 1 million m³);
- By displacement speed - from extremely slow (displacement speed less than 16 mm/year) to very slow (displacement speed more than 16 mm/year, but not more than 1.6 m/year).

According to the mechanism of slope deformation development, the landslide developing in the area under consideration refers to landslides with a complex (combined) displacement mechanism. In the upper part of the landslide massif, where the Escalator Gallery is located, a series of three to four landslide steps are clearly distinguished, which is typical for insectious landslides of shear (slip). The lower, lingual part of the landslide massif, characterized by bulging shafts formed in the channel part of the Moscow river valley, refers to extrusion landslides.
More than once attempts have been made to restore the escalator gallery, but no project has been implemented. In 2018, it was decided to restore the facility. In 2019, old structures were dismantled. Figure 1 shows the gallery during the dismantling process and Figure 2 shows the project of the new gallery.

![Figure 1. Gallery in the process of dismantling.](image1)

![Figure 2. Project of new gallery.](image2)

The site of the supposed emergency recovery works on the escalator gallery is located in Moscow. Geomorphologically, the slope in question is located in the valley of the Moscow River on the steep right bank.

The stability of the slope has been monitored since 1962. During the observation period from 1976-2005, in connection with the deformation of the old escalator gallery, regime observations were carried out both on the gallery and the slope. In 2004-2005, comprehensive observations of slope
stability were organized on the western side of the old escalator gallery. Analysis of the observation results showed that on the upper part of the landslide ledge, slow plastic deformations develop with a displacement rate of 5-7 mm/year, which, when peak values are reached, can go into shear deformation. Also, slight soil shedding is visually observed.

The emergency condition of the escalator gallery is the result of landslide processes.

The foregoing indicates a high probability of the development of deep deformations and an unstable state of the slope.

The need for this study is motivated by the construction of a new escalator gallery, under conditions of constant creep of the slope, as well as by the fact that the base of long-term observations of landslide slopes, especially not stabilized, is insufficiently accumulated. Of course, at the moment, there is a regulatory framework, but it does not give us constructive solutions and design justifications on such slopes.

In [6], the natural stability of the slope was considered depending on the choice of the calculation method; in our article, the issue of the stability of the slope during the construction and operation of a new gallery is solved.

2. Methods
The slope stability calculations at the construction site of the new Escalator Gallery were made taking into account measures to strengthen it and evenly distributed loads from the weight of the designed inclined gallery and vestibules. The calculation was performed by a numerical simulation method in a flat setting using the specialized Plaxis 2D software package. The soil foundation model adopted in the calculations is the Hardening Soil model of soil (HS model), which is the most universal for modeling soil soils.

The HS model includes the following input parameters:

- $E_{50}$ is secant stiffness module from the test in the stabilometer;
- $E_{oed}$ is tangential stiffness module from the odometer test;
- $E_{ur}$ is stiffness modulus during unloading/reloading from tests in a stabilometer;
- $m$ is an indicator of the degree of dependence of stiffness on stresses;
- $\phi$ is the angle of friction;
- $c$ is clutch;
- $\Psi$ is the angle of dilatancy;
- $\nu_{ur}$ is Poisson's ratio during unloading/reloading;
- $p_{ref}$ is reference voltage;
- $K_{0nc}$ is value of K0 during normal soil compaction;
- $R_f$ is the fracture coefficient.

The calculation model is a flat section passing through a slope in the longitudinal direction. Rows of piles and nagels were modeled in a flat task using the “Embedded Pile Row” element, taking into account the pitch and diameter of the pins.

When calculating the slope, we compared the slope stability coefficient without anti-landslide measures and taking into account various options for strengthening it.

3. Results
To date, it is planned to build a new escalator gallery, which raises the question of strengthening the landslide section. The authors proposed several options for strengthening the slope as anti-landslide measures, based on the use of drill piles and drill-injection gels to reinforce the ground massif.

3.1. Calculation of the slope without actions against landslide
The authors also calculated the stability of the soil mass without using various options of engineering protection. The results of this calculation are shown in Figure 3. The stability factor was 1.125.
3.2. Option strengthening No. 1.
In the first version of the action to strengthen the landslide slope, the reinforcement elements are located only in the lower part of the inclined section of the slope. They are nagels with a diameter of 120 mm and length 24 m. The inclination of reinforcing elements is 20° to the horizon. The stability coefficient as a result of the calculation was equal to 1.213. Figure 4 shows the calculation results of this reinforcement variant. However, this option is not acceptable because the slope is constantly moving and large horizontal stresses occur in its lower part, and nagels will be to take up horizontal loads that they will not be able to withstand.

3.3. Option strengthening No. 2.
In the second version of strengthening the landslide slope, drilling-injection nagels with a diameter of 150 mm were used as elements of strengthening the massif on the area under the stations and 120 mm on the inclined area of the gallery location. The length of nagels with a diameter of 150 mm is 30 m,
120 mm - 24 m. The angle of inclination nagels under galleries is 20° to the horizon. The calculation resulted in a stability factor of 1.418. The result of the calculation is shown in Figure 5.

![Figure 5. Calculation resulted in a stability factor of 1.418.](image)

### 3.4. Option strengthening No.3.
In the third version of strengthening the landslide section, the authors propose drilling piles with a diameter of 850 mm under the upper and lower vestibules as strengthening elements, and in the intermediate section of the slope it is proposed to use nagels with a diameter of 120 mm. The stability coefficient as a result of the calculation was equal to 1.79. Figure 6 shows the calculation results of this reinforcement variant.

![Figure 6. Calculation results of reinforcement variant.](image)

### 3.5. Option strengthening No.4.
The fourth version of strengthening the landslide section involves using only drilling piles with a diameter of 850 mm under the upper and lower vestibules as elements of strengthening the soil mass. The use of reinforcing elements of the inclined section of the gallery is not envisaged. As a result of the calculation, the stability coefficient was 1.779. The result of the calculation is shown in Figure 7.
Figure 7. Result of the calculation, the stability coefficient was 1.779.

Table 1 shows the stability factors for all calculation variants.

| Option                                      | Stability factor |
|---------------------------------------------|------------------|
| Calculating the slope without strengthening | 1.125            |
| Option strengthening No.1.                  | 1.213            |
| Option strengthening No.2.                  | 1.418            |
| Option strengthening No.3.                  | 1.79             |
| Option strengthening No.4.                  | 1.779            |

A comparative analysis was also performed with [20]. In this work, measures were taken to strengthen the slope, corresponding to the "Strengthening Option No. 2" in our article. According to [20], the slope stability coefficient is 1.303, which is 9% less than our results.

4. Conclusions

1. As a result of the calculations carried out, it was found that the most suitable option, which ensured the greatest stability of the slope, was the strengthening option No. 3 with the stability coefficient of the 1.79. But less material-intensive and economically feasible is the option of strengthening No. 4, whose stability factor is least by 0.01.

2. Also, this calculation does not take into account dynamic loads acting both during the construction of the gallery and during its operation, so it is necessary to organize and carry out local monitoring of landslide processes.

3. As already mentioned, the slope is constantly moving and large horizontal loads occur, which will best perceive piles with a diameter of 850 mm located under the gallery stations.

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