3D Modelling of the Landslide Slope Stability with Seismic Effect

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Abstract. Three-dimensional analysis is an important and actively developing area in calculating the stability of slopes. The work was based on the results of the stability analysis of the landslide slope on the left side of the Kuban river valley above the Krasnogorsk hydropower station. The calculations were performed using the limit equilibrium methods in the three-dimensional formulation of the problem, taking into account the seismic effect. In this paper seismic effects were taken into account using the pseudostatic method. Based on the performed mathematical modelling it was shown, that direction of seismic impact changes not only the safety factor but also the spatial position of the potential landslide massif. This study proves the importance of three-dimensional calculations in the development of engineering protection measures against landslide processes.

1. Introduction

The problem of establishing the seismic effects role in the loss of slopes stability and landslide activity is one of the key tasks in seismically active regions, because Seismic-induced landslides are usually larger and more catastrophic. However, at present its consideration in modeling the slope stability is carried out as a rule in a flat statement of the problem solution. And the problem of safety factor (Fs) dependence on the intensity of an earthquake was mainly solved. The influence of the seismic impact direction on the slope was given unreasonably little attention. The cause was rather limited practice of calculating the slope stability in the three-dimensional formulation. However, recently the situation has begun to change. A large number of methods for three-dimensional stability calculations have been developed on the basis of both limiting equilibrium and continuum mechanics methods [1, 2, 3, 4].

In addition to the influence of seismic effects intensity on Fs, in 3D modeling it is possible to select areas in which the loss of stability may occur during unavoidable future earthquakes. Solving this problem is of crucial practical importance for the assessment of both landslide and seismic hazards, which in its turn is a prerequisite for ensuring the safety of the population and various industrial and infrastructure facilities in regions with high landslide hazards.

This article discusses the impact of seismic impact the direction on the Fs value and on the potentially unstable landslide massif position.

2. Object of study

The study was based on the stability analysis results of the landslide slope on the left side of the Kuban river valley. (Figure 1). The left bank Krasnogorsk landslide develops in the left side of the...
valley where the river exits from the Caucasus Mountains on the foothill plains. The area currently affected (from 2016) by slope deformations is about 6 hectares (figure 2). The length of the landslide in the displacement direction reaches 400 m. The width of the landslide body in the head part is up to 200 m, tapering in the middle part to 120 m. According to drilling data the thickness of landslide body is about 15–18 m. The total volume of rocks involved in displacements is estimated at 1 million cbm.

Figure 1. Location of the research site (red rectangle).

Figure 2. General view of the left-bank Krasnogorsk landslide from the right bank of the Kuban river.

The upper part of the geological section in the considered territory is formed by the Jurassic sediments of the Plensbachen, Aalenian and Bajocian ages. The Plensbachen formations are formed by packs of rhythmically and non-rhythmically interbedded wavy and gently sloping layers of fragile easy-weathering sandstones and siltstones, which have a high water-holding capacity and become
softened when watering. Deposits of the Aalenian age lay with erosion and angular disagreement on the Plensbachen age deposits. They are represented by weathering-resistant layered and slanting-stratified, dolomitic sandstones with intercalations of limestone. The Bajocian formations are composed of low-strength, lightweight, weathered argillites. Bajocian deposits were involved in the displacement during the formation of the modern landslide on the considered site. According to the mechanism of the landslide process the considered landslide refers to slip landslides [5, 6]. Considering the presence of several landslide stages, it should be attributed to landslides of a complex type.

Study area is characterized by rather high seismicity. Estimated seismicity for unchanged ground conditions on the surface is 8 points on the MSK-64 scale.

The calculated seismic inertia forces FH acting on the soil mass in the horizontal direction in pseudostatic analysis [7, 8] are written as:

\[ FH = 0.5\alpha \cdot W \]  

where \( \alpha \) is the ratio of the calculated ground acceleration \( ag \) to the acceleration of gravity; \( W \) is the weight of the sliding massif.

3. Methods and approaches

The slope stability calculation was performed by one of the limiting equilibrium methods [9] - Morgenstern-Price method [10, 11], in a three-dimensional statement [12, 13]. Accounting of seismic effects can be performed on the basis of dynamic [14, 15, 16] or pseudostatic [17] methods. In this paper pseudostatic analysis was used.

The geotechnical model for its use in the stability calculations was designed on the basis of engineering geological survey results. The final geomechanical scheme used in the calculation is shown in figure 3.

**Figure 3.** 3D-geomechanical model.

When modelling the landslide array stability 4 scenarios were considered:

1. stability calculation without seismic impact;
2. stability calculation with seismic effects acting along the slope dip;
3. stability calculation with seismic effects acting perpendicular to the slope fall direction (northeast - southwest);
4. stability calculation with seismic effects acting perpendicular to the slope fall direction (south-west - north-east).

4. Results discussion
The main task in calculating the slope stability is to find the position and shape of the critical sliding surface (which is characterized by the minimum stability coefficient).

Figure 4 shows the simulation results for the scenarios described above.

Figure 4. Simulation results: a) stability calculation without seismic impact (Fs-1.04); b) stability calculation with seismic impact, directed along the slope dip (Fs - 0.831); c) calculation of stability with seismic effects acting perpendicular to the slope fall direction (northeast - southwest) (Fs-0.967); d) calculation of stability with a seismic effect acting perpendicular to the slope fall direction (south-west-northeast) (Fs-0.996). The red arrow shows the direction of the seismic impact.

Analysis of the calculation results showed that a change in the direction of seismic impact affects both the safety factor of the landslide massif and the spatial position of the potential collapse block.
In natural conditions excluding seismic effects (figure 4a) according to the calculation the slope is in the state of limit equilibrium (Fs $= 1.04$), which agrees well with the data from the field survey (figure 5). The potential zone of collapse is confined to the break edge of an activated landslide and is traced down the slope.

![Figure 5. Spurs and cracks in the head of an active landslide.](image)

When a seismic impact is directed along the dip of the slope, it becomes unstable (Fs $< 0.831$). At the same time, the position of the potential collapse zone does not have major changes. It is also confined to the break of a landslide and is traced down the slope.

When the seismic impact is directed perpendicular to the slope fall, the slope also loses stability (Fs $< 0.967$ for the design scenario 3 and Fs $< 0.99$ for the design scenario 4). This effect is very problematic to obtain in a two-dimensional calculation. In this case, the nature of potential collapse zone varies. For the calculated scenario 3 a potential active block with a minimum Fs generally retains its position, but in comparison with scenarios 1 and 2, when calculating according to scenario 4 it changes its position significantly, shifting in the direction of the seismic force.

Thus, the analysis of potential sliding surfaces with minimal Fs (Figure 4) showed that two groups of potentially unstable zones can be distinguished. The first group is associated with seismic impact in accordance with design scenarios 1-3, the second - with design scenario - 4. It is significant that the same magnitude, but different in sign, directed perpendicular to the fall of the slope, affects its stability in different ways (Fs in the third scenario - 0.967, in the fourth - 0.996).

The high impact of the site by the landslide process predetermines the need of engineering protection measures development. The performed mathematical modeling proves that during their development it is necessary to take into account not only the value of Fs, but also the change in the position of the potentially unstable zone of the landslide slope for various directions of seismic impact.

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