Application of Geophysical Methods in Landslide Danger Assessment within the Slopes of Kremlin in Nizhny Novgorod

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Abstract. The article discusses the experience of applying a complex of methods of engineering geophysics (seismic exploration and electrical prospecting) in assessing landslide hazard and the opportunities of their use for engineering protection measures on the slopes of Nizhny Novgorod. The article substantiates the urgency of the problem for the slopes of Nizhny Novgorod, provides an example of research and calculations on a slope area subject to deformation due to the activation of landslide processes. The main features of the landslide formation process study on the slopes of historical natural and technical systems are presented. The experience of using the engineering geophysics methods is summarized and the prospects for their use on the studied slopes are assessed.

1. Introduction

Nizhny Novgorod is situated in the central part of Russia at the confluence of the Oka and Volga rivers. The city has almost 800 years of history. The Oka River divides the urban area into two parts: the eastern elevated Nagornaya located on the right banks of the Oka and Volga at the northwestern tip of the Volga upland - the Dyatlov Gory, and the western (along the left bank of the Oka and the right bank of the Volga) lowland. The center of Nizhny Novgorod is a witness of many historical events and is an architectural monument. The Nizhny Novgorod Kremlin, monasteries and churches are located in the picturesque place of the two great rivers confluence (figure 1).
2. The relevancy of the problem
The problem of landslide formation on the slopes of Nizhny Novgorod is of particular importance due to the large number of historical and architectural monuments that may suffer with the process activation[3]. In February 2020 employees of the Engineering Geology Department of (together with Ecotechkontrol LLC) carried out works to assess the slope stability as part of the Eternal Flame memorial reconstruction. Calculations have shown that the slopes are unstable or are in a state of limit equilibrium. In practice this meant that the process could be activated at any moment. In May 2020 local displacements of earth masses occurred on the slopes under the fortress walls of the Kremlin (figure 2).
The process of studying and forecasting landslide hazards in this situation is further complicated by the fact that the studied slopes[17] are located within the so-called historical natural and technical systems (HNTS)[4], which have certain specificity of the landslide formation process[1]. Among them it is necessary to consider the relief and hydrogeological conditions changes, the technogenic soils (cultural layer) formation on the slope which predetermines the sliding surface[2], etc.

3. Description of geotechnical conditions

3.1. Location and relief
The studied slopes are located on the banks of the Oka and Volga rivers[7]. Geomorphologically it is the watershed plateau between the Oka and Volga, dissected by ravines. The modern relief is changed, the territory is partly built up. Absolute elevations vary from 56 m at the water's edge to 132 m. The climate of the region is moderatly continental with cold snowy winters and moderately hot relatively short summers. The average annual air temperature is positive and is + 3.8 °C. The average height of snow cover during the winter reaches 58 cm, snow melting begins in the third decade of March and ends in mid-April. The average annual precipitation is 560 mm, 70% falls on the warm season (April-October), the average daily amount of precipitation for the same period is 55 mm.

3.2. Geological cross-section
From a geological viewpoint the area under consideration is located within the Tokmovskaya system of arched uplifts in the northwestern part of the Volga-Kama anteclise. The Volga slope is composed of rocks of the Tatar stage of the Upper Permian (P2t) and overlapping formations of the Quaternary system (deposits of problematic genesis (prQII-III) and technogenic (artificial) soils (tQIV)).

The technogenic soils (tQIV) are represented by brown loam with black humus and inclusions of hard yellowish-brown sandy loam; brown hard clay, with nests of sand and inclusions of crushed stone of carbonate rocks (5-15%)[5]. According to the method of laying technogenic soil is characterized by a dry method of filling, classified as a dump of soil. It is heterogeneous in composition and distribution and characterized by uneven density and compressibility. The thickness of the filled soil is about 1.70 - 4.30 m.

In the middle part of the section undivided Upper-Middle Quaternary deposits of problematic genesis (prQII-III) are identified, they are represented by a stratum of loess-like loams and sandy loams. They are macroporous highly calcareous micaceous with thin interlayers of sand, of semi-hard and hard consistency, with single interlayers of thick-plastic consistency[6]. The top of the layer is eroded. Upper Permian deposits (P2t)[9]. are represented by Upper Permian sediments: variegated hard clay with single inclusions of semi-solid consistency, fractured and lumpy with inclusions of clayey siltstone, clayey marl, interlayers of polymictic sand with sandstone gravel and crushed stone on clay cement, inclusions of nests and interlayers of carbonaceous silt, crushed stone[19]. The exposed thickness of the layer is 2.50 - 25.30 m.

Based on the results of field work and laboratory tests of soils 6 engineering and geological items were determine (see figure 3)
Figure 3. The geomechanical model of the slope[8]

1 - technogenic soil - loam with inclusions of sandy loam, sand, clay, heterogeneous; 2 - loess loam, semi-hard, subsiding; 3 - loess loam, semi-hard, non-subsiding; 4 - loess sandy loam, solid, non-subsiding; 5 - clay variegated, heterogeneous, hard; 6 - clay siltstone, semi-solid.

4. Engineering and geophysical research

Among the geophysical methods for studying landslide slopes methods of electrical prospecting and seismic prospecting[11], radon method, micro-magnetic prospecting, and the well inclination angle of measuring are used. With their help the most important geological boundaries are mapped, the lithological composition of soil layers is clarified, the position of the groundwater level is determined[12], zones of increased fracturing and water saturation are localized, the physical and mechanical properties[15] of soils and the anisotropy of properties characteristic of landslide bodies are clarifie.

Among the seismic exploration methods, the Refracted waves, the method of reflected waves (RW), in the modification of the common depth point (RW CDP) are used. While the implementation of the refraction method circular and azimuthal soundings is actively used. Seismic tomography (ST) which has become a natural continuation of the refracted wave method, is being actively introduced into the landslide bodies studying practice.

Electrical prospecting is carried out by resistance methods and ground penetrating radar. Vertical electrical sounding (VES) and its azimuthal version are used - circular sounding (CVES), symmetric electrical profiling (SEP) and a relatively new technology – electric tomography (ET), which has absorbed the advantages of VES and SEP, combining them with high speed and detailed data obtaining.

Radon method is used for structural and geodynamic mapping - the identification of soil blocks and zones with different levels of activity associated with landslides.

When implementing micromagnetic survey, proton and quantum magnetometers of increased sensitivity and special processing techniques are used, a dense regular observation network with a step of 1–2 m. Magnetic prospecting is used to identify areas of increased fracturing associated with landslide processes. Inclination measuring is used to monitor the landslide process in observation wells.

Geophysical profiles are laid along the contours of the relief, perpendicular to the landslide slope, and a profile along the slope must also be designed. Depending on the size of the studied bodies and the complexity of their structure, the distance between the profiles is 10 - 25 m.
After analyzing the engineering and geological conditions and the results of topographic survey, it was decided to use two methods that have proven themselves well in the study of landslide processes - seismic and electric tomography. The result of performing seismic tomography is shown in the figure.

In general, the largest amount of data was obtained precisely by seismic tomography using horizontally polarized shear waves (SH) [13-14, 18-19]. The seismic survey was carried out along the contours of the relief, on relatively flat areas (most often on landslide terraces), according to the standard Y-Y scheme for SH waves. The main feature for identifying already displaced landslide bodies and their blocks was a decrease in the shear wave velocity (to a level of 110-150 mps), provoked by the weakening of bonds between soil particles. Work was carried out perpendicular to the main profiles according to the Y-Y scheme, designed to excite and receive longitudinal waves. Seismic tomography on longitudinal waves made it possible to establish the position of the level of ground waves in the section of the slope and to identify zones of high humidity. In addition, landslide bodies were distinguished by an increased coefficient of anisotropy (up to 1.1 - 1.2), which is explained by the redistribution of stresses.

According to the results of electric tomography it was possible to confirm the position of the groundwater level, to map more precisely the zones of increased water saturation and identify lithological layers in the section - loam, sandy loam and sand.

![Figure 4](image-url) 

**Figure 4.** The result of inversion of seismic tomography data (Zond2DST software). Vertical - depth, horizontal - profile points. Shear wave velocities (VS) are displayed in color. The profile passed across two landslide bodies; they were distinguished by a local decrease in speed.

## 5. Conclusion

When studying landslide slopes in cramped conditions in historical territories geophysical methods, although they are indirect, have several important advantages. They are quite simple to use and at the same time provide important engineering and geological information necessary for adequate modeling and assessment of the stability of landslide slopes. On the studied area of the slope, the most informative were the methods of seismic and electrical tomography.

## 6. References

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