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Methodology for Monitoring the Risks of Collapse of Roads, Buildings and Structures Due to Soil Erosion

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Abstract
Soil erosion poses a significant risk to the stability of roads, buildings, and structures, especially in geologically hazardous areas. This study proposes a methodology for automated monitoring of soil erosion to reduce the risk of structural collapse. The developed dynamic-geophysical monitoring system, integrated with advanced sensors and real-time data analysis, enables early detection of soil instability. The system was tested on various structures, including residential buildings in Kaliningrad and a roadbed in Ulyanovsk, which were exposed to dynamic loads such as vibration from nearby construction and transport. The monitoring system successfully identified soil imbalances, allowing for timely intervention and improved stability. By utilizing this approach, construction projects can better assess risks, optimize engineering measures, and ensure the safety of infrastructure in high-risk areas. This methodology not only enhances risk management for soil erosion but also offers a reliable solution for long-term monitoring in geologically sensitive zones.

Keywords: Soil Erosion, Dynamic Geophysical Monitoring, Emergency Risk Management.

Introduction

Development of the new territories for construction of the roads, buildings and structures leads to the fact that more and more buildings and structures are located in geologically hazardous areas. Soil massifs also can get out of the balance due to dynamic and static loads from nearby construction and transport facilities. The loss of the balance and stability of soils leads to subsidence, landslides, disruption of hydrological regimes, suffusions, karst phenomena, increased vibration and, as a result, to an increased risk of collapse of roads, buildings and structures.

The technology of dynamic-geophysical monitoring of the "soil-structure" system, developed with the participation of the authors, makes it possible to timely identify the risk of collapse of controlled objects from soil erosion.

The proposed technology was been tested on the following objects:

- Residential buildings with rolls and deformation cracks in Kaliningrad, which arose from the impact of vibration during the bank protection works on the river embankment;
- Buildings in the Imereti Valley, Adler, with subsidence of foundation slabs relative to each other;
- A school in Moscow exposed to increased vibration from a nearby metro tunnel;
- Roadbed in Ulyanovsk due to the lack of slope drainage in the area of road slippage and increased vibration load from the railway transport and heavy vehicles (Fig. 1).

Figure 1: Sliding of the roadbed in Ulyanovsk due to inefficient drainage and increased vibration from the railway transport and heavy vehicles.

Successful approbation of the proposed technology proved the possibility, in addition to automated monitoring of engineering structures of buildings and structures in geologically hazardous areas, to monitor soil erosion that may result emergence of a risk zone exposed to this hazard. This monitoring should be done at the stage of exploration and construction, as well as afterwards - in potentially hazardous places.

Soil erosion poses a significant threat to infrastructure, leading to structural instability and failure. This study focuses on developing a dynamic-geophysical monitoring system to address this critical issue and improve safety in geologically hazardous areas.

The proposed technology for integrated dynamic geophysical monitoring is represented by the measuring and analytical system (IAS) (Fig. 2 and Fig. 3), installed in the zone of possible geological hazards and consisting of: a computer with a specialized program that allows you to receive and, according to special criteria, process and analyze digital data from sensors installed in the controlled area; multichannel analog-to-digital converter (ADC); three-component acceleration sensors, tilt sensors, water level and pore pressure sensors in the soil; cable or radio channel data transmission system from sensors to ADC. The composition and quantity of the necessary elements of the IAS is determined depending on the object and the number of controlled parameters.

The criteria for assessing the stability of soil mass, developed with participation of the authors, make it possible to determine at an early stage from days to several hours state of unstable soil balance. A sensitive parameter of the rigidity of structural systems is fluctuations of the soil mass, which alike structural systems, depend on their mass and rigidity.

Methodology

The IAS implementation includes a detailed site survey to determine sensor placement, ensuring optimal data accuracy. Calibration procedures involve testing under controlled conditions to validate sensor sensitivity and reliability

Figure 2: Installation of a mobile system for dynamic and geophysical monitoring of a landslide-prone section of the road in Ulyanovsk

Figure 3: Data collection point for dynamic and geophysical testing of the impact of dynamic and background loads on the soil mass in the area of the construction site, residential complex under construction and the road at the landslide.

Ground mass oscillations can be determined by solving the following differential equation [1-3]:

$$T_1 = \frac{l^2}{\pi^2}\sqrt{\frac{m}{EJ}}. \quad (1)$$

where
- T 1 - the period of oscillation of the object, sec;
- l is the length of the object , m;
- m is the linear mass of the object, kg/m;
- E - modulus of elasticity, N / m 2 ;
- J is the moment of inertia of the object m 4 .

For a soil mass, the equation relating its vibrations to geometric and physical-mechanical parameters can be represented as follows:
- $T_1=2,63\times H\sqrt{(\rho/G)}$, where
- ρ- is the density of the considered block of the soil massif;
- G - is the shear modulus of the soil mass;
- H- is the height of the soil block.

Therefore, by controlling the oscillation period of an object or a soil mass, you can control their rigidity, including degree of watering.

The monitoring data on the landslide-prone slope, obtained with participation of the authors, are presented in fig. 3.4

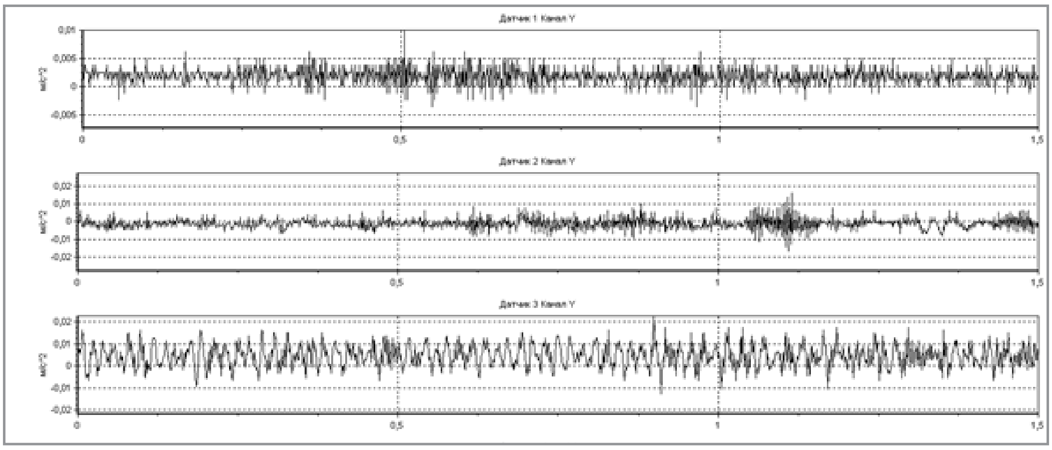

Figure 3: Acceleration of a landslide-prone section in Ulyanovsk along the Y axis during the passage of a freight train

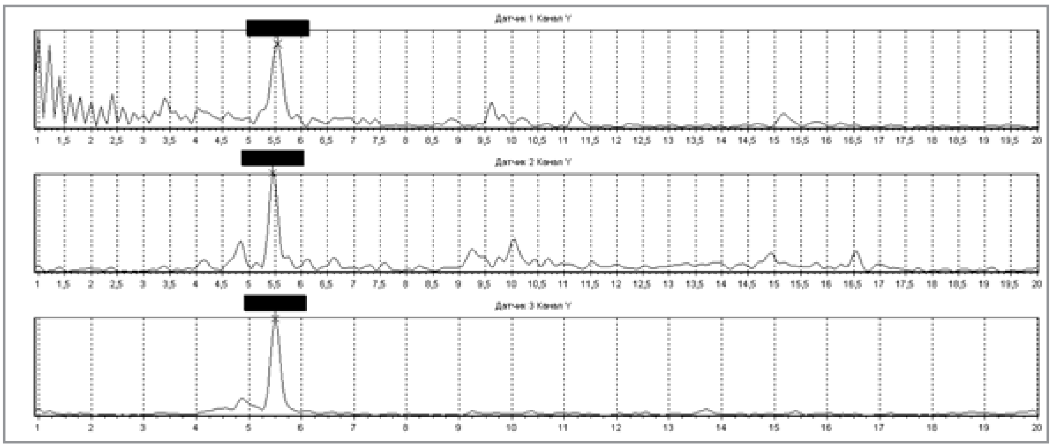

Figure 4: The spectrum of vibrations along the Y axis. The appearance of dangerous low-frequency vibrations during the passage of a freight train on a landslide-prone section in Ulyanovsk.

Table 1: Results of dynamic-geophysical tests of the soil mass under different types of dynamic impact.

Object and types of measurements	A x, m / s ²	A y, m/s ²	A z, m / s ²
Ground massif, background influences	0.003 0.015 0.03 0.004	0.003 0.01 0.01 0.004	0.004 0.005 0.005 0.003

Ground massif, passing trams	0.004 0.01 0.03 0.008	0.004 0.01 0.01 0.003	0.004 0.02 0.005 0.004
Ground massif, passage of 35 tons of truck	0.01 0.042 0.03 0.006	0.01 0.042 0.03 0.006	0.01 0.09 0.005 0.002
Ground massif, passage of 35 tons of truck	0.005 0.022 0.022 0.15	0.004 0.02 0.015 0.3	0.005 0.01 0.01 0.2
Soil massif, piling 5 tons hydraulic device	0.006 0.045 0.03 0.52	0.0041 0.03 0.03 1.25	0.0052 0.015 0.01 0.6
Ground massif, the passage of the train	0.02 0.01 0.02	0.005 0.01 0.015	0.005 0.0075 0.0075

Table 2: The period of natural oscillations of the soil massif in a wet state and after intensive drainage work

No.	The state of the soil mass during the performance of dynamic geophysical measurements.	T x , sec	T y , sec	T z , sec
1	Heavily flooded	0.078	0.078	0.078
2	After drainage equip-ment, the soil is moder-ately moist	0.05 High frequency shifted	0.05 Shifted to the high frequency region	0.05 Shifted to the high frequency region

Analysis of the data presented in Table No. 1 shows that the amplitude of accelerations of a landslide-prone slope caused by the passage of a railway freight train is 6.6 times higher than the background oscillations of the slope during the passage of heavy vehicles. The periods of slope oscillations during the passage of a train and trucks are shifted to the region of resonant frequencies (0.1-0.2) sec, which increases the risk of loss of stability of the soil mass of the slope.

The results of comparing the dynamic-geophysical parameters of the wetted soil mass (Table No. 2) with the soils after the drainage system equipment, and the lowering of the groundwater level in the landslide-prone area show that the periods of natural oscillations along all measurement axes have shifted to the high-frequency region.

Comparison data show how sensitive dynamic and geophysical parameters are to changes in the state of soils. Efficiently performed work on lowering the groundwater level increased the rigidity of the soil mass, reduced deformation processes and increased stability of the landslide-prone slope.

The given measurement results show that the greatest accelerations and, consequently, displacements of the soil mass because dynamic loads created by the movement of freight trains and heavy vehicles.

Accelerations arising from the impact of driven foundation piles during the construction of a building on the top of a slope are fixed in the region of the landslide at the background level and, therefore, they could not be the cause of its descent.

The main reason for the landslide was a strong moistening of the soil mass, which led to its vibrations with a natural oscillation period of 0.078 sec along all axes and resonant dynamic effects from the passage of trains and heavy vehicles.

The example considered in the article shows that the reduction of the landslide hazard of a soil massif on a slope can be achieved by: equipping drainage and storm systems that ensure the effective removal of groundwater; control of the state of the soil mass for the timely determination of dynamic and geophysical parameters and the exclusion of the occurrence of resonant phenomena from dynamic influences; complex monitoring of the "soil-construction" system.

Thus, the proposed technology of integrated soil-structure monitoring can provide timely warning of the risk of soil erosion and thereby reduce the likelihood of destruction of roads, buildings and structures by taking appropriate measures. Monitoring measurements will allow at the design stage to ensure the correct choice of rational engineering measures to improve the stability of the "soil-construction" systems, and at the operation stage - to ensure control over the effectiveness of their work.

Discussion

The findings demonstrate that the proposed monitoring system significantly enhances the predictive accuracy of geotechnical risks. Compared to conventional methods, this approach integrates real-time data analytics, providing a proactive solution for infrastructure stability.

Conclusion

This study highlights the critical role of advanced monitoring systems in preventing infrastructure failures. Future research should focus on integrating machine learning algorithms to further enhance predictive capabilities.

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Annotion

Proposed technology for automated monitoring of the possible soil erosion designated to reduce the risk of collapses of roads, buildings and structures.