Landslide Dynamics and Deterministic modelling of landslide hazards at the large scale

O.M. Ivanik, V.V. Shevchuk, D.V. Kravchenko, L.V. Tustanovska, K.P. Hadiatska *(Taras Shevchenko National University of Kyiv)*

SUMMARY

Deterministic modelling of landslide hazards at the large scale are performed according to various methods and approaches based on quantitative assessment methods and taking into account geological, geomorphological and meteorological factors of the landslide process. One of the important criteria for assessing the slope stability is the stress-strain state of the rock mass. Calculations of the stress-strain state of a slope with variable parameters are carried out. To investigate and understand the behavior and dynamics of landslide processes, the Unmanned Aerial Vehicles (UAVs) have been used. The development of a three-dimensional model of the landslide in the Krasnyk village, Ukrainian Carpathians allowed to trace the dynamics of the landslide process and to determine the elements and morphometric parameters of the landslide body. These parameters were used to perform a detailed geomorphological and geological analysis aimed at identifying the main geomorphological features and geological causes associated to instabilities and as base for the design of the mitigation works to stabilize the slopes of this site.

Introduction

Landslides are a significant hazard to property and livelihoods, causing millions of hryvnas worth of damage annually in Ukraine. It is important to understand landslide hazards in order to mitigate their risks. Geohazards are still very high in the mountainous regions such as Carpathians, despite the progresses related to the comprehension and modelling of hazardous processes at large scale. The sustainable development of mountainous areas and safety to the people require reliable study and modelling of hazardous processes. A major threat is induced by all types of gravity processes (e.g. landslides, debris and earth flows) which are triggered in these areas and which represent one of the most destructive natural hazards in the Carpathian region.

Slope movements (e.g. landslides) are dynamic systems that are complex in time and space and closely linked to both inherited and current preparatory and triggering controls. It is not yet possible to assess all factors for multi-dimensional behavior and formation of complex landslides, although considerable progress has been made in classification and choice of rheological models. Successful decision making process of landslide hazard forecasting and development of measures is impossible without quantitative assessment of the slope stability and determination of failure characteristics of rock complexes, which are based on a set of mathematical models characterizing different stages of landslide process.

Local prediction of landslide hazards and assessment of the slope stability

Recently most of the calculations of the slope stability on the basis of various techniques are carried out using specialized software that allows to solve time-consuming problems (*Kaliukh et al., 2018a, 2018b; Trofymchuk et al., 2017).* It has become possible to perform calculations for slopes with complex lithological and stratigraphic characteristics, variable pore pressure, to take into account additional loads and elements of structural strengthening of slopes. Visual control of data, as well as graphical output of results allow to analyze the whole process, not just calculate the coefficient of the slope stability. The most common software products for assessing the slopes stability are based on engineering calculations and using boundary equilibrium methods. They are PC-Slope, Infinite Slope, Simple Slope and others. The studies of the magnetic properties of soils are promising for the landslide hazards assessment (*Menshov et al., 2012, 2014*).

Strength loss can occur instantly during the process of failure, through loss of cohesion, liquefaction of granular material or remoulding of clay. Further loss of strength can occur during movement, including rock joint roughness reduction, shearing in deposits, sliding surface liquefaction, frictional heating, loss of internal coherence of the landslide body, and entrainment of water (*Hungr, 2007*). It is very important to study the behavior of rock complexes, in order to facilitate predictions of the existence of landslides for landslide hazard assessment.

Since the stress-strain state of the rock mass is the one of the important criteria for assessing the stability of the slope, this study is an important step to assess the formation of landslides (*Ivanik et al., 2019*). The solution of this problem includes several stages, covering a comparative analysis of values and indicators of strength where, according to geological data, we can expect the danger in terms of the stability of zones and contacts; detection of the formation of zones of big stresses that form near the surface of the slopes, along large cracks, etc.; determining the influence of tectonic and other cracks of different directions on the stress distribution in the rock mass; analysis of changes in stress distribution in the deposits as a result of erosion in recent times and at the ratio in the river valley.

In recent years, powerful software complexes have been developed and intensively improved for solving large classes of problems in the mechanics of continuous media by numerical methods. These software packages are a practical tool for calculating the stress-strain state of rocks using numerical methods (*Ivanik et al., 2017, 2019b*). Preferably, these programs use the finite element method to

calculate the parameters of the stress-strain state. The following software has been developed: Plaxis 2D (Plaxis 3D Foundation, Plaxis 3D Tunnel), FLAC 2D (FLAC 3D), FLAC Slope, ABAQUS and others. It should be noted that these software packages have certain versatility, but with certain problems are applied to specific conditions, not always able to take into account important factors of processes, in particular, the anisotropy of the environment. This requires the use of special approaches to modeling the stability of landslide slopes, characterized by special conditions of the structure of the rock mass and types of geohazards.

Example

Here is an example of determining the stress-strain state of rocks within a landslide slope, taking into account a number of geological and geomorphological factors. Problem statement, features of geological structure and physical and mechanical properties of rocks determine the degree of schematization (formalization) of calculations.

The main summary factors that are taken into account in the development of physical and mathematical models and calculations based on the algorithmic scheme of the mathematical model are following:

- water saturation;
- temperature gradients within the considered array;
- the existence of the Earth's gravitational field;
- consolidated type of rocks with its thermomechanical characteristics such as Young's modulus, Poisson's ratio, coefficient of linear expansion, density, yield strength;
- boundary conditions;
- geometric characteristics (dimensions, slope angle).

Within the mathematical model, the considered phenomenon is described as a thermoelastic-plastic equilibrium of an isotropic matrix under the action of mass (gravitational field of the Earth) and surface forces applied to it, an inhomogeneous stationary temperature field. In addition, it is believed that the Young's modulus at each point of the matrix depends on temperature and water saturation.

As a result of application of the calculation-analytical module on an estimation of influence of gravitational processes calculations of the stress-strain state of a slope with variable parameters are carried out. The landslide slope section (Figure 1) in the village of Krasnyk, Verkhovyna district, Ivano-Frankivsk region was a test site. A catastrophic situation as a result of heavy precipitation in July 2008 has been observed, which led to the formation of a series of landslides and the negative consequences on the environment and economy. In June 2020, the landslide was reactivated. This landslide occurred in a complex topographic environment. The landslide-prone area is located on the south-western part of the village of Krasnyk within 3200-3500 m of the Iltsi-Burkut road. The research area is located on the continuation of the Rozhanka skyba of the Slavsko-Verkhovyna subzone of the Krosno structural-facial zone of the Carpathians. The site covers the left slope of the Black Cheremosh River, which belongs to the Prut River Basin. The morphometric parameters of the site are as follows: its width along the road is more than 50 m, length is more than 100 m. The slope steepness within the site is variable and ranges from 10 to 55º.

Figure 1 *Landslide in Krasnyk village, Verkhovyna district, Ivano-Frankivsk region, Ukraine*

The landslide occured again in June 2020 due to heavy precipitation. 7 settlements and the border service were left without transport connections. Field surveys in 2010 determined that the landslide has a complex structure and is actually a combination of several landslides of different structure, differing in both the mechanism of formation and their expression in the landform.

The mass movement in the flysch deposits led to the subsequent involvement in the process of displacement of Quaternary formations, which caused the formation on the slope of different age landslides, characterized by specific morphological features and scale of manifestation. The main stage of the landslide process is characterized by the formation of a slide of structural genesis with the formation of later slides in a quasi-homogeneous medium. In general, the described slide belongs to the category of combined slides of complex multistage nature. Based on the classification features, it can be attributed to structural landslides of consecutive type, and complicated by second-order forms formed in a quasi-homogeneous medium represented by delluvium-colluvium Quaternary deposits.

We analyze the rock mass composed of loamy deposits, which are characterized by modules of total deformation of 11 and 7.2 MPa, respectively, in the dry and water-saturated state with a Poisson's ratio of 0.3 and a density of 1700 kg / m^3. Taking into account the parameters of the shear slope, the distribution of the main stresses, which vary from 2 to 20 MPa, is determined. Analysis of the distribution of main stresses within the landslide slope indicates the spatial differentiation of this indicator, and proves the increase in stresses in the lower part of the slope, which explains the current activity of the landslide process and determines the greatest hazard in this part.

To investigate and understand the flowing behavior of landslide processes, the Unmanned Aerial Vehicles (UAVs) are applied. Low altitudes (from 50 m to 150 m) aero-photogrammetric surveys are commonly used to generate high resolution data by using light drones. Unmanned Aerial Vehicles (UAVs) remote sensing has the following advantages: real time measurement, flexibility in usage, high resolution, low costs, and easy to collect data in unfavorable environmental conditions (Chang Chun et al., 2011). The development of a three-dimensional model of the landslide allowed to trace the dynamics of the landslide process and to determine the elements and morphometric parameters of the landslide body (Fig. 2). These parameters were used to perform a detailed geomorphological and geological analysis aimed at identifying the main topographic features and causes associated to instabilities and as base for the design of the mitigation works to stabilize the slopes of the hill.

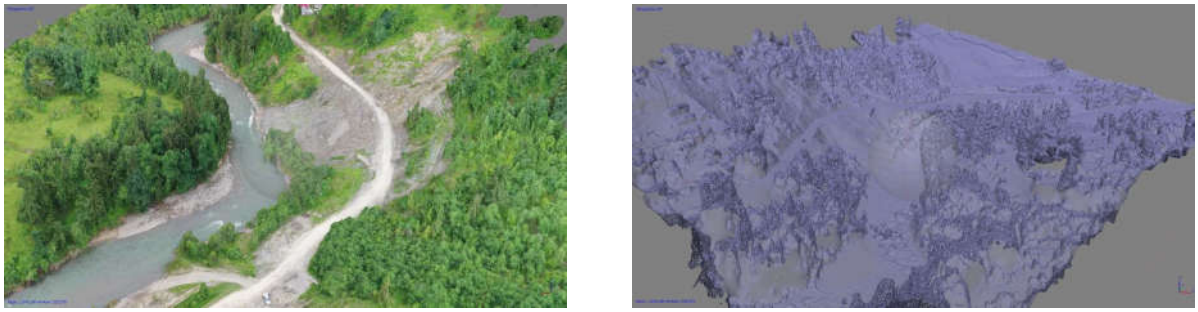

Figure 2 *Three-dimensional model of the landslide in Krasnyk village, Verkhovyna district, Ivano-Frankivsk region, Ukraine*

To prevent the further activation of this process, it is necessary to build the protective wall and a drainage system along the road with a depth of not less than 0.5 m.

Conclusions

Deterministic modelling of landslide hazards at the large scale are performed according to various methods and approaches based on quantitative assessment methods and taking into account geological, geomorphological and meteorological factors of the landslide process. One of the important criteria for assessing the slope stability is the stress-strain state of the rock mass, so to

assess the landslide hazard, these studies are an important step. Calculations of the stress-strain state of a slope with variable parameters are carried out. To investigate and understand the flowing behavior of landslide processes, the Unmanned Aerial Vehicles (UAVs) have been used. The development of a three-dimensional model of the landslide in the Krasnyk village, Ukrainian Carpathians allowed to trace the dynamics of the landslide process and to determine the elements and morphometric parameters of the landslide body. These parameters were used to perform a detailed geomorphological and geological analysis aimed at identifying the main topographic features and causes associated to instabilities and as base for the design of the mitigation works to stabilize the slopes of the hill.

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