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Simulation of mass movement during landslide processes in the agricultural landscape

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A R T I C L E I N F O

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A B S T R A C T

The use of mathematical modeling methods makes it possible to quantitatively characterize in detail some or other agroecologically hazardous process, which is necessary for its subsequent quantitative forecast and control. This method is currently being actively developed and has great prospects. The study of slope processes, especially such catastrophic manifestations as avalanches, landslides and mudflows, is necessary for their forecast and the Rhodope design of protective structures.

1. Introduction

Among natural disasters, landslides are in fourth place after droughts, floods and earthquakes. A landslide is the displacement of a part of rocks to a lower hypsometric level while maintaining contact with a fixed base. Landslide processes are successive changes in the composition, state and properties of the soil mass from the moment of its origin and movement to another level up to complete attenuation, manifested in deformations of the constituent rocks. Landslide elimination is a long-term process that takes on average 6 to 10 months. Experience shows that preventing landslides, for instance, on highways, is much cheaper than eliminating their consequences, because this leads not only to a multiple increase in construction costs, but also to economic losses as a result of restricting traffic, etc. More than half of all material damage caused by landslides is associated with errors made in calculating the stability of slopes and designing landslide protection structures. The main quantitative indicator of the stability of slopes is the safety factor, which shows the ratio of the retaining and displacement forces acting on the slope section. If the shifting forces are greater, the slope is considered unstable and a landslide forms.

A significant number of mathematical models are used to analyze the dynamics of mudflows, avalanches and landslides [1-6]. To assess their applicability to a specific process, as well as to develop new models, it is necessary to analyze and typify the existing ones. The classification and examples of mathematical models of mudflow and slope processes, as well as schemes for representing the flow of matter for various types of models are analyzed in detail in [1-4]. At the same time, an important component is determining the scale and dynamic characteristics of these

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processes and phenomena, for which various methods are used: field observations, remote sensing methods, experimental and mathematical modeling (each of them has its own field of application and its own degree of accuracy).

The authors of [1, 2] analyze methods for calculating the relative weights of the hazard for a territory, which showed that the method of pairwise comparisons is the most appropriate for determining the relative hazard for a territory. In [4], an approach to the synthesis of expert systems is proposed, which makes it possible to estimate the probability of occurrence of elementary unwanted (basic) events at potentially dangerous objects. The study of landslide processes is an relevant issue, both during the construction of new facilities and during the operation of those already built. Systematic monitoring of landslides allows preventing the destruction of slopes (both natural and artificial), prevent the threat of emergency situations in buildings and structures, and therefore avoid human casualties.

The relevance of the problem for Azerbaijan is due to the presence of many territories prone to landslide processes. Assessment of the stability of natural and artificial slopes is one of the main objectives of engineering and geological surveys for almost all types of construction. But no other branch of engineering activity depends so closely on the stability of natural slopes and slopes of artificial excavations as the construction of roads and railways.

The development of reliable landslide protection structures is a very difficult problem, the successful solution of which is impossible without a quantitative assessment of the stability of slopes and the development of slope deformations, based on a set of mathematical models describing the various stages of the landslide process. However, despite the fact that the beginning of studies of landslides falls on the sixties of the last century, obtaining such an estimate is associated with great difficulties: the complexity and multifactorial nature of landslide phenomena, the abundance of variables that determine the course of landslide processes, the absence of physically substantiated dependencies giving a rigorous mathematical description of these processes. The safety factor is defined as the ratio of the retaining and displacement forces. The magnitude of the displacement forces is determined by the magnitude of the weight force acting on the soil, the angle of inclination of the slope surface. The magnitude of the force of the weight acting on the ground and the angle of the slope surface can be determined with sufficient accuracy.

Massive activation of landslides is observed under special meteorological conditions − a large amount of precipitation. The acuteness of the problem of the activation of landslides is that their catastrophic manifestations can cause huge economic losses.

2. Problem statement and solution

All factors determining the formation and development of landslide processes are divided into three groups:

1) permanent or unchanging (geological structure and relief) territories surrounding the region;

2) slowly changing (modern tectonic movements, climate, hydrogeological, geocryological conditions, vegetation, soils);

3) rapidly changing (meteorological, hydrological, seismic conditions, economic activity).

The separation of landslides according to their mechanism is carried out at the same hierarchical level; six different types of landslides are distinguished from each other: sliding, squeezing, floating, flow, subsidence and liquefaction. The peculiarities of the engineering-geological conditions of the territories and, first of all, the composition, structure and properties of the rocks of the stratigraphic-genetic complexes composing the slopes, determine the unevenness both on the whole on the globe and in individual geological regions, in particular, in the specific conditions of the territory, according to the peculiarities of the technogenic impact on the geological environment, it can be divided into two orographic zones: the mountain system of the Greater Caucasus in the north, and the foothill plain in the south.

The most common genetic types of landslides in the territory are sill flows and mud flows, earth flow and liquefaction slides. Mud flows or liquefaction slide are the most common. They are characterized by a close relationship with the weathering crust of rocks [3, 4].

The complexity and variety of relief forms of rock massifs and intermontane troughs, its seismotectonic activity, anisotropy and heterogeneity of properties and structure, a basin of mountain rivers, the influence of ground and underground engineering structures, an intensively and chaotically expanding network of tourist facilities and other geomechanical factors predetermine the unsteadiness of stresses and strains and rock displacement. For this reason, it becomes very important to assess the quantitative and qualitative indicators of the distribution of these fields of rock massifs with mountainous relief, which directly depends on the issues of geomechanics related to the calculation and forecast of the stress-strain state of mountain ranges, the determination of the parameters of the displacement process and the protection of structures from underworking. The relevance of these problems is due to the numerous cases of dangerous geomechanical and geodynamic phenomena that took place in mountainous areas.

One of the areas of research work carried out in research centers is the development and use of mathematical models for determining and predicting the stress-strain state of rocks described by various mechanical models that most fully reflect the specifics of mining and geological conditions, as well as the results of instrumental observations of deformation of the earth's surface.

The change in the porosity coefficient under loading and unloading for most porous rocks can be represented as a linear function of the logarithm of hydrostatic stress σ:

$$\mathrm{T}e = N - \lambda \cdot ln\sigma; e = e_k - k \cdot ln\sigma, \quad (1)$$

where λ, k are the angles of inclination of straight lines, respectively, when loading and unloading; N, e_k are the initial values of the porosity coefficient. In this case, the deformation of the specimen during unloading and repeated loading is considered elastic. Volumetric plastic compression deformations will occur when stresses go beyond the boundary of the yield surface Ap_c, which has the shape of an ellipse with a center offset from the origin. According to the associated law of plastic flow, the yield surface is also the surface of the plastic potential, i.e.

$$F = Q = \frac{q^2}{M^2 \cdot \sigma} + \sigma - p_c = 0, \quad (2)$$

where F, Q denote, respectively, the fracture criterion and the plastic potential; M is the critical state line (CSL) parameter of the form $q = M \cdot \sigma$.

The appearance of volumetric plastic deformations ε_v^p means hardening of the material, i.e. expansion of the area of elasticity Ap_c according to the law

$$p_c = p_{c0} \cdot exp\left(\frac{1 + e_0}{\lambda - k}\right) \cdot \varepsilon_v^p \quad (3)$$

In the region of low normal stresses (at $\sigma < p_c/2$), hardening of the material is impossible and the appearance of plastic deformations is due to the rupture of the material during shear or tension. In the diagram, the σ-q form of the shear fracture criterion is similar to the Coulomb-Mohr criterion:

$$F = q - \sigma \cdot tan\varphi^* - C^*, \quad (4)$$

where $tg\varphi^* = \frac{6sin\varphi}{3 - sin\varphi}$; $C^* = p_c \cdot (M - tg\varphi^*) / 2$.

Under tension, the fracture criterion is written in the form

$$F = -\sigma 3 - \sigma p = 0,$$

where σ_p is tensile strength.

With the destruction of the material from shear or tension, plastic deformations of an increase in volume (dilatancy) appear. In this case, the parameter p_c, according to (3) decreases and the elastic region decreases with it, i.e. softening occurs.

Most often, the movement of earth masses on the slopes occurs due to a combination of a number of reasons. Depending on the specific conditions and reasons, rock movements on the slopes have different dynamics and different forms of manifestation: they can be superficial or deep. Displacements of grassy turf and weak deluvium belong to the surface: slipouts, eath flows, slumps can be distinguished among them. All of them are caused by the saturation and liquefaction of rocks with water, they usually are periodical and have a low speed of movement.

Deep displacements, or landslides proper, capture the slope to a depth of sometimes tens of meters. The dynamics of the landslide process in this case depends not only on the reasons for the development of landslides, but also on the geological structure of the slope (composition of rocks, conditions of their occurrence, layering, etc.).

The classification of landslides provides for the identification of the actual landslides, as well as their varieties in the form of flows and landslides – avalanches. Landslides proper occur only by earth masses sliding along the slope. The sliding plane is usually located at considerable depths (many meters). Flows mean a displacement of earth masses in a small area (hundreds of square meters) due to water saturation of the upper layers. The depth of the sliding plane is up to 1 m. They are typical for the spring season. Landslides and avalanches represent the displacement of earth masses simultaneously in the form of sliding and collapsing. The are typical for steep slopes.

Considering that soils in every region have their own genetic characteristics, it is preferable to apply in forecasting mechanical and mathematical calculations of the stability of slopes and artificial slopes in soft rocks.

The study of slope processes, especially their catastrophic manifestations such as landslides, avalanches and mudflows, is necessary for their forecast and design of protective structures.

The Navier-Stokes motion equation system is obtained by considering the sum of forces acting on an elementary infinitesimal volume of fluid $dx{\cdot}dy{\cdot}dz$ in the form of a parallelepiped, where dx, dy and dz are the sides of the parallelepiped in the direction of the x, y and z coordinates, respectively (or x_1, x_2 and x_3, respectively). As is known, normal σ_i (acting on the area perpendicular to the i axis) and tangential stress τ_{ij} (acting on the area y perpendicular to the j axis, $j{\neq}i$) and τ_{ik} (acting on the area perpendicular to the k axis, $k{\neq}i$, $k{\neq}j$) act on per unit area of the wall of a given volume in the direction of the i axis. The gravitational force g_i in projection onto the i-axis also acts on per unit mass of a given volume. After adding the forces together and applying Newton's second law, as well as reducing both sides of the equation by $\rho{\cdot}dx{\cdot}dy{\cdot}dz$, we obtain a formula for the projection of the velocity υ_i and stresses $\sigma_{i.}$ τ_{ij} , τ_{ik} on the i-axis:

Given that according to Newton's formula

$$\sigma_i = -p + 2n\frac{\partial Vi}{\partial Xi}; \tag{5}$$

then we obtain a system of the Navier-Stokes of equations of motion for a viscous incompressible fluid, which is the basis for all mathematical models of the type under consideration. The depth-integrated form of these equations is called the Saint-Venant equations.

The application of the equations of motion of a viscous incompressible fluid to mudflows and landslides requires the introduction of additional forms of the dependence of the tangential stresses τ on the velocity υ, which differ from expression (3). In particular, the most common rheological formula of Coulomb and Velmi:

$$\tau = \rho g H \left(\cos\alpha + \frac{v^2}{gR}\right)(1 - r_u) tg\varphi + \rho g \frac{v^2}{\xi} \quad (6)$$

where g is gravitational force; H is the flow depth; α is the slope angle; R is the radius of curvature of the flow bed in the vertical longitudinal section; r_u is coefficient of soil pore pressure; φ is the angle of friction; ξ is the turbulence coefficient.

For models of the considered type, the following is required: a digital model of the relief, given initial and boundary conditions (flow characteristics such as velocity and pressure) and information about changes in these characteristics over time. Data are also required on the physical properties of the flow substance − density, viscosity, angle of friction, and modulus of elasticity. As a result of the operation of the models, fields of values of the physical parameters of the flow of substance at different moments of time are obtained − the vectors of velocity, depth, pressure, forces, etc. The indicated values are presented in the form of maps or digital models. The information obtained as a result of modeling can be useful when considering the zones of distribution of mudflows and landslides, as well as when taking protective measures.

3. Conclusion

In this paper, analytical solutions of the equations of landslide motion in the form of a Riemann wave have been obtained within the framework of various models. It has been shown that if the dynamics of a landslide is described by a model of a viscous layer, then nonlinear effects develop faster on the crest of the landslide.

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