УДК 551.2.3
DOI: http://doi.org/10.17721/1728-2713.101.03

M. Lubkov, Dr. Sci. (Phys.-Math.), Senior Researcher
e-mail: mikhail.lubkov@ukr.net
Poltava Gravimetric Observatory of Institute of Geophysics
of Ukraine National Academy of Science
27/29 Mysoedova Str., Poltava, 36014, Ukraine

MODELING OF LANDSLIDE DEFORMATIONS UNDER THE ACTION OF GRAVITY

(Представлено членом редакційної колегії д-ром геол. наук, проф. О.М. Іванік)

Nowadays, there are actual problems associated with destructive slope processes under the influence of gravity load. Indeed, gravitational slope processes, together with other erosion and tectonic processes, contribute a lot to the formation of the modern relief and at the same time very often complicate the rational using of the corresponding territory. Landslide processes can be distinguished among the most dangerous gravitational slope processes. These processes are characterized by widespread distribution and significant material losses and human casualties to which they lead. Due to its social importance and practical engineering significance, the problems of studying gravitational shear processes have a long history. Therefore, many works are devoted to these problems, but from another hand, the cases of strict mathematical and mechanical description and determination of certain quantitative mechanisms and criteria for the development of sliding gravitational processes have been considered in a rather limited way. In presented work on the base of variational finite-element method, we calculate the rotational deformation and failure criteria of a wide class of three-dimensional heterogeneous anticlinal geostructures under the gravity load conditions. The simulation results show that the shear deformation of anticlinal geostructures under the influence of gravity depends on the shape, size of the structure, and mechanical properties of the rocks that make up these geostructures. We have established that more compact geostructures are subjected to the smallest deformation. In the solid geostructures that retain elastic properties, the deformations are inversely proportional to the degree of rock stiffness, and a decreasing in the curvature radius of the geostructure leads to an inversely proportional increase in the deformation of the corresponding geostructure. We have shown that in order to maintain resistance to shear soil gravity failure, anticlinal geostructures cannot be completely composed of rocks softer than semi-solid dispersed soils. It was established that the resistance to shear gravity soil failure of heterogeneous anticlinal geostructures is mainly determined by the rigidity of the internal bearing rocks, while the influence of the stiffness of the external soft rocks is relatively insignificant and has a non-linear character.

Keywords: computer modeling, landslide anticlines deformations, gravity load.

Introduction and statement of the problem. Nowadays, the problems associated with destructive slope processes under the influence of gravity load remain relevant. Indeed, gravitational slope processes, together with other erosion and tectonic events, play important role in the formation of the modern relief. These processes at the same time very often complicate the rational using of the corresponding territory. Landslide processes can be distinguished among the most dangerous gravitational slope events. These processes are characterized by widespread distribution and significant material losses and human casualties to which they lead. Landslide processes, among other gravitational slope processes, are characterized by the presence of a soil shifting without loss of continuous contact between the moving and stationary parts of the massif (*Григоренко и др., 1992; Осипов, 1999; Dikay et al., 1996; Bell and Maud, 2000; Pathak et al., 2008*). Thus, for the description of gravitational shear soil processes, we can neglect the consideration of soil massif gaps with other rheological effects and limit ourselves to the application of the theory of elasticity for a solid medium. Gravitational soil shear processes are very numerous and have various geological forms (*Bell and Maud, 2000; Hunter and Fell, 2003; Van Asch et al., 2007*). Therefore, it's impossible to embrace all cases, so we limit ourselves to consideration of rotational gravitational soil shear processes for three-dimensional heterogeneous anticlinal geostructures. This case is common enough and can be very useful for practical applications.

Analysis of latest investigations. Due to its social importance and practical engineering significance, the problems of studying gravitational shear soil processes have a long history. Many works are devoted to these problems, among which the following can be singled out (*Вэй, 2010; Кюль, 2017; Ниязов, 2015; Пендин и Фоменко, 2015; Фоменко, 2012; Hunter and Fell, 2003; Zhang et al., 2006; Van Asch et al., 2007; Pathak et al., 2008; Cruden and Lan, 2015*). Due to the ambiguity and variety of natural and practical cases of gravity shear soil processes, these works mainly relate to the definition of general geological and engineering classifications, qualitative criteria and mechanisms of destructive events**.** Computational models are simple enough and mostly limited by analytical and semi-analytical approximate methods.

Pinpointing unresolved issues. On the other hand, the cases of strict mathematical and mechanical description and determination of certain quantitative mechanisms and criteria for the development of sliding gravity processes, especially rheological numerical methods, have been considered in a rather limited way. The variational finite-element method proposed in this paper for solving the problem of the elasticity of multilayer orthotropic shells, taking into account the shear rigidity (*Лубков, 2015*) adequately allows calculating the deformation processes, mechanical behavior and failure criteria of a very common class of three-dimensional heterogeneous anticlinal geostructures in the conditions of gravity load. This approach has important theoretical and practical interest and provides a number of advantages compared to existing methods.

Setting objectives. The aim of the article is modeling of shear soil processes under gravity loads of wide class of heterogeneous anticlinal geostructures on the base of elaborated variational finite-element method.

Research part and findings validated. Mathematical formulation and solving problem. Consider the deformation of the anticlinal geostructure in the form of the upper half of a fragment of a three-layer cylindrical shell, which is rigidly fixed at the ends and is under the influence of gravity. To describe the deformation of the considered anticlinal geostructure, which consists of rocky or dispersed soil rocks (*Трофимов, 2005; Zhang et al., 2006; Van Asch et al., 2007*) we will use the theory of multilayer orthotropic elastic shells of rotation taking into account shear rigidity (*Лубков, 2015*). We will consider the shell in the curvilinear coordinate system (s, φ, z), which we will consider rigidly fixed with a large solid rock massif. Here s, φ – coordinates along the surface of the shell; z is the shell thickness coordinate.

Displacements along the s, φ, z coordinates for the j-th layer of the shell can be represented in the form (*Лубков, 2015*):

$$u_j = u_0(s,\varphi) + z u_1(s,\varphi);$$
$$v_j = v_0(s,\varphi) + z v_1(s,\varphi); \quad (1)$$
$$w_j = w_0(s,\varphi) + z w_1(s,\varphi),$$

here u_0, v_0, w_0 – displacement components of the middle surface of the shell; u_1, v_1 – rotation angles of the middle surface normal relatively coordinate lines φ = const, s = const accordinally, w_1 – compression of the middle surface normal of the shell. Let's make the Lagrange functional (*Лубков, 2015*), which expresses the potential mechanical energy of the considered geostructure, which is under gravitational load conditions:

$$\tilde{W} = \frac{1}{2}\sum_{j=1}^{3}\int_{h_j}\int_{S}[E_{ss}{}^j \varepsilon_{ss}{}^{j2} + E_{\varphi\varphi}{}^j \varepsilon_{\varphi\varphi}{}^{j2} + E_{zz}{}^j \varepsilon_{zz}{}^{j2} + 2E_{s\varphi}{}^j \varepsilon_{ss}{}^j \varepsilon_{\varphi\varphi}{}^j +$$
$$+2E_{sz}{}^j \varepsilon_{ss}{}^j \varepsilon_{zz}{}^j + 2E_{\varphi z}{}^j \varepsilon_{\varphi\varphi}{}^j \varepsilon_{zz}{}^j + 4G_{s\varphi}{}^j \varepsilon_{s\varphi}{}^{j2} + 4G_{sz}{}^j \varepsilon_{sz}{}^{j2} +$$
$$+4G_{\varphi z}{}^j \varepsilon_{\varphi z}{}^{j2} - 2\rho_j g w_j](1+\frac{z}{R_g})^2 ds\, d\varphi\, dz - \quad (2)$$
$$-\int_{\varphi_1}^{\varphi_2}(T_s u_0 + T_{s\varphi} v_0 + Q_s w_0)d\varphi - \int_{s_1}^{s_2}(T_{\varphi s} u_0 + T_{\varphi} v_0 + Q_{\varphi} w_0)ds.$$

here R_g – the radius of curvature of the geostructure; g – gravity acceleration; S – surface area of the geostructure; h_j – thickness of the j-th layer of rocks of the geostructure; ρ_j – density of the j-th layer; $\varepsilon_{\alpha\beta}{}^j$ – components of the strain tensor of the j-th layer; $E_{\alpha\beta}{}^j$ – modulus of elasticity of the j-th layer; $G_{\alpha\beta}{}^j$ – components of the shear modulus of the j-th layer; $T_\alpha, T_{\alpha\beta}$ – forces acting on the contour of the geostructure in the tangential directions to its surface; Q_α – forces acting on the contour of the geostructure in directions perpendicular to its surface. The boundary conditions of the problem make up on the rigid fixation of the fragment of the considered geostructure at its ends.

For resolving the presented problem of deformation of the geostructure under the influence of gravity, we will use the finite element method based on the variational principle of Lagrange, which expresses the minimum potential mechanical energy of the system (*Лубков, 2015*):

$$\delta\tilde{W}(u_0, v_0, w_0, u_1, v_1, w_1) = 0\,. \quad (3)$$

For resolving the variational equation (3), we use the nine-node isoparametric quadrilateral shell finite element with a curved surface (*Лубков, 2015*). A curvilinear coordinate system (s, φ, z) is used as a global coordinate system, that is, a system where all finite elements (on which the research area is divided) are combined. As a local coordinate system, where every finite element form functions are constructed, normalized coordinate system (ξ, θ) is used. At the making of the finite element form functions, which approximate within each element the components of displacements $u_0, v_0, w_0, u_1, v_1, w_1$, for satisfaction of the conditions of smoothness and convergence of the finite-element solution, we use algebraic and trigonometric polynomials (*Лубков, 2015*):

$$u_0 = \sum_{i=1}^{9} N_i u_{0i};\; v_0 = \sum_{i=1}^{9} N_i v_{0i};\; w_0 = \sum_{i=1}^{9} N_i w_{0i};\; u_1 = \sum_{i=1}^{9} N_i u_{1i};$$
$$v_1 = \sum_{i=1}^{9} N_i v_{1i};\; w_1 = \sum_{i=1}^{9} N_i w_{1i}. \quad (4)$$

$$N_1 = H_1(\theta)P_1(\xi);\; N_2 = H_1(\theta)P_2(\xi);\; N_3 = H_3(\theta)P_2(\xi);$$
$$N_4 = H_3(\theta)P_1(\xi);\; N_5 = H_1(\theta)P_3(\xi);\; N_6 = H_2(\theta)P_2(\xi);$$
$$N_7 = H_3(\theta)P_3(\xi);\; N_8 = H_2(\theta)P_1(\xi);\; N_9 = H_2(\theta)P_3(\xi). \quad (5)$$

$$H_1(\theta) = \frac{\sin(\theta-\theta_2) - \sin(\theta-\theta_3) + \sin(\theta_2-\theta_3)}{\sin(\theta_1-\theta_2) - \sin(\theta_1-\theta_3) + \sin(\theta_2-\theta_3)};$$
$$H_2(\theta) = \frac{\sin(\theta-\theta_3) - \sin(\theta-\theta_1) + \sin(\theta_3-\theta_1)}{\sin(\theta_2-\theta_3) - \sin(\theta_2-\theta_1) + \sin(\theta_3-\theta_1)};$$
$$H_3(\theta) = \frac{\sin(\theta-\theta_1) - \sin(\theta-\theta_2) + \sin(\theta_1-\theta_2)}{\sin(\theta_3-\theta_1) - \sin(\theta_3-\theta_2) + \sin(\theta_1-\theta_2)};$$
$$H_j(\theta_k) = \begin{cases} 1, j = k \\ 0, j \neq k \end{cases};$$

$$P_1(\xi) = \frac{1}{2}\xi(\xi-1);\; P_2(\xi) = \frac{1}{2}\xi(\xi+1);\; P_3(\xi) = 1-\xi^2. \quad (6)$$

The finite-element algorithm for solving the variational problem (3) is following. At the first stage, in the local coordinate system (ξ, θ), we make approximation of all displacements and deformations from functional (2), which are functions of the displacement components $u_0, v_0, w_0, u_1, v_1, w_1$, with the help of formulas (4–6). Also, In the local system we carry out analytical integration within each shell layer, and then make summation over the entire package of the shell layers. At the second stage, the functional (2) is variated relatively all nodal displasement components and the corresponding variations are equalized to zero. As a result, for each finite element, we obtain a linear algebraic system consisting of 54 equations. At the third stage, in the global coordinate system (s, φ, z), the summation of local linear systems of algebraic equations takes place over all the finite elements into which the shell is divided. Also, we make here the formation of the global system of linear equations. Calculation of double integrals over the area of the shell is carried out by numerical integration based on Gauss's quadrature formulas (*Лубков, 2015*). We resolve the global system of linear algebraic equations using the Gauss numerical method (*Лубков, 2015*). As a result, the displacement components $u_0, v_0, w_0, u_1, v_1, w_1$ can be determined at all nodal points of the finite element grid. Then components of displacements, deformations, stresses, and other interesting values can be determined from the found nodal displacement components at any point of the finite element, i.e., at any point of the considered shell geostructures.

Modeling of shear processes of anticlines under gravity loads. At modeling of the gravitational shear processes of anticlinal geostructures, we will consider the deformation of the upper half of a three-layer cylindrical shell under the action of gravity with the following parameters: the radius of the shell is 100 m, the thickness of the three layers of the shell is 10 m, respectively, the angle from the horizontal in the positive direction (counter-clockwise) is $\pi/2$. The average density of the considered rocks will be considered equaled to 2300 kg/m^3. Firstly, we will consider the shear deformation (movement in the angular direction), along the surface of the slope of homogeneous anticlinal geostructures. In fig. 1 we consider the case of rocky soil (*Трофимов, 2005*) with the following elastic properties: Young's modulus E = 7•10^{10} Pa, Poisson's ratio μ = 0.3. Fig. 2 shows the case of solid dispersed soil rocks: E = 7•10^{9} Pa, μ = 0.3. Fig. 3 shows the deformation of anticlinal geostructures, which also consist of solid dispersed rocks, when the radius of curvature of the structure is 80 m. Fig. 4 shows the deformation of geostructures composed of semi-solid dispersed soil rocks (E = 2•10^{9} Pa, μ = 0.35) and rigid plastic dispersed soil rocks (E = 10^{8} Pa, μ = 0.4) (*Трофимов, 2005*). In fig. 5 we consider the deformation of anticlinal geostructures, with the layers which consist of various combinations: 1) hard; 2) semi-hard; 3) tough-plastic; 4) plastic (E = 5•10^{7} Pa, μ = 0.4); 5) soft-plastic (E = 2 •10^{7} Pa, μ = 0.35); 6) flow-plastic (E = 2•10^{7} Pa, μ = 0.45) dispersed soil rocks (*Трофимов, 2005*).

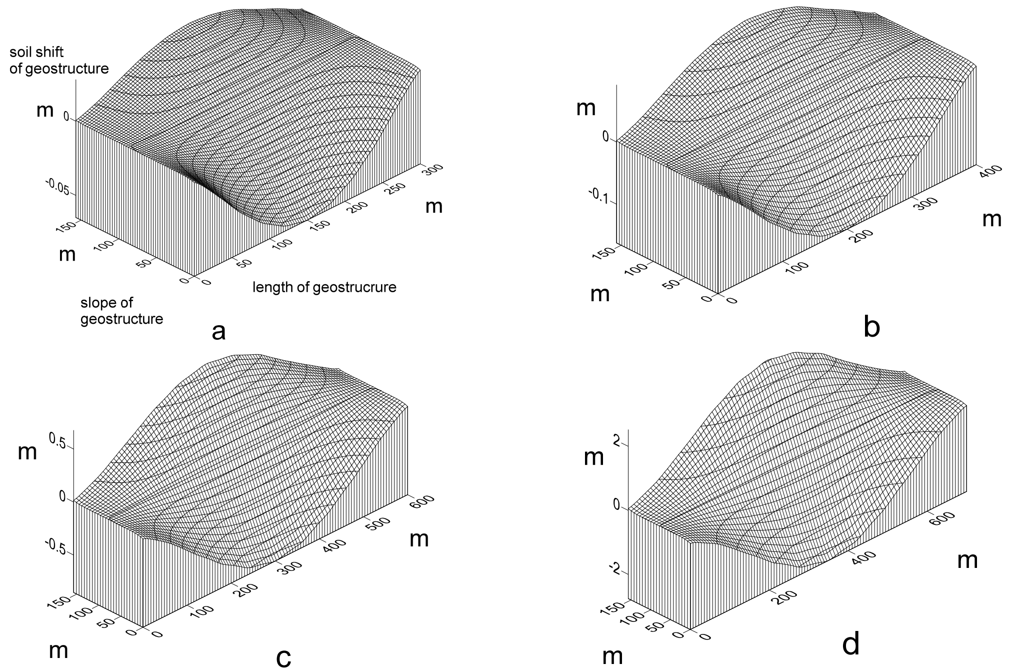

Fig. 1. Landslide deforming of anticline geostructures, which consist of rigid rocks, under gravity forces action:
a – length of the geostructure 300 m; b – 400 m; c – 600 m; d – 700 m

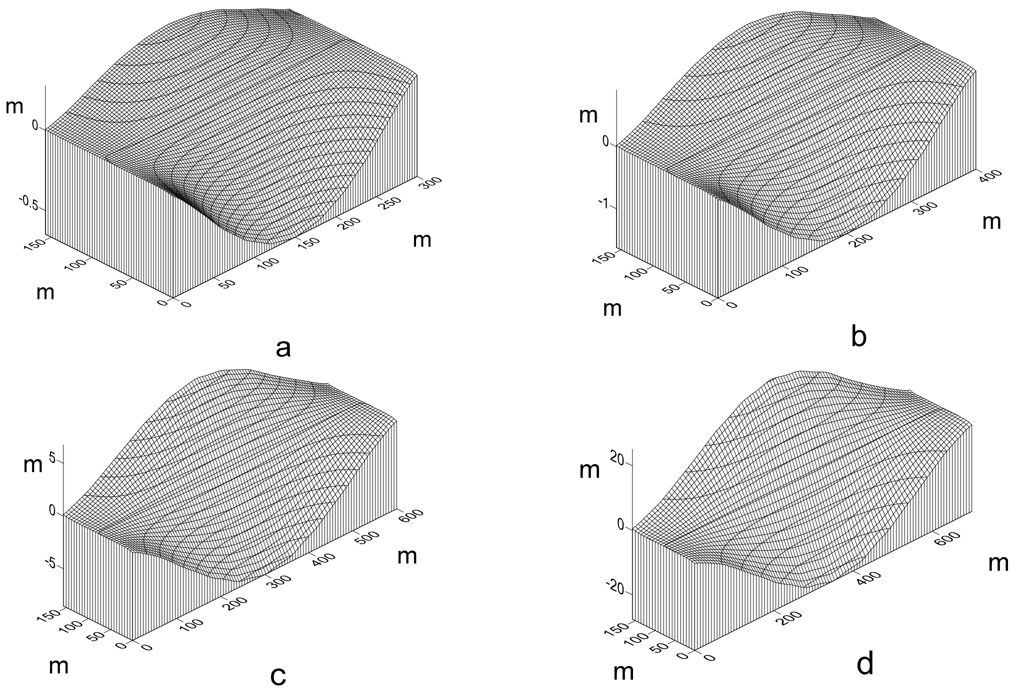

Fig. 2. Landslide deforming of anticline geostructures, which consist of rigid dispersing grounds, under gravity forces action:
a – length of the geostructure 300 m; b – 400 m; c – 600 m; d – 700 m

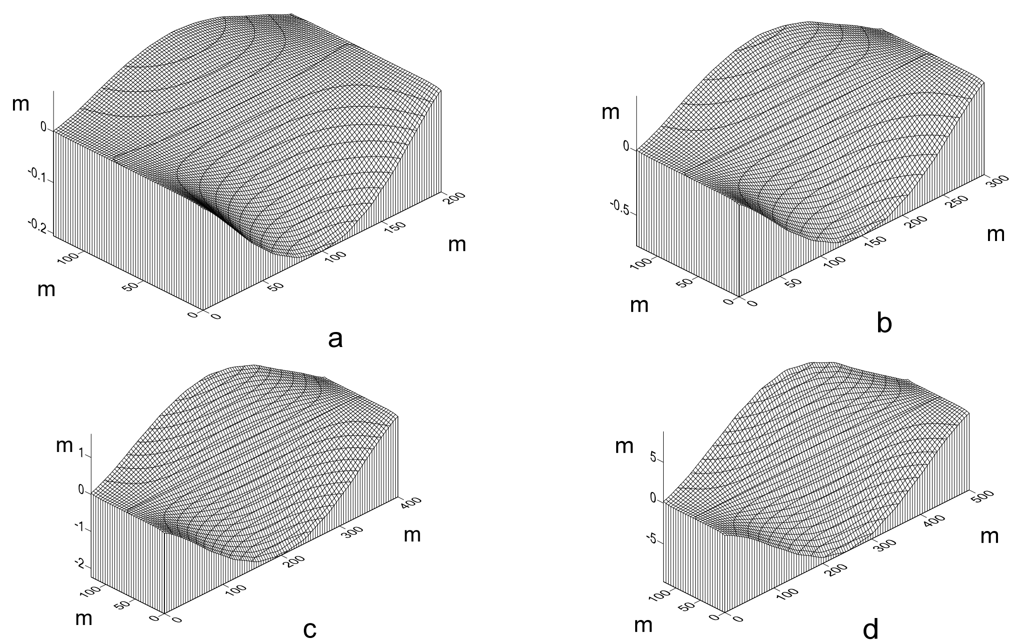

Fig. 3. Landslide deforming of anticline geostructures, which consist of rigid dispersing grounds, under gravity forces action (anticline curvature radius is 80 m):
a – length of the geostructure 200 m; b – 300 m; c – 400 m; d – 500 m

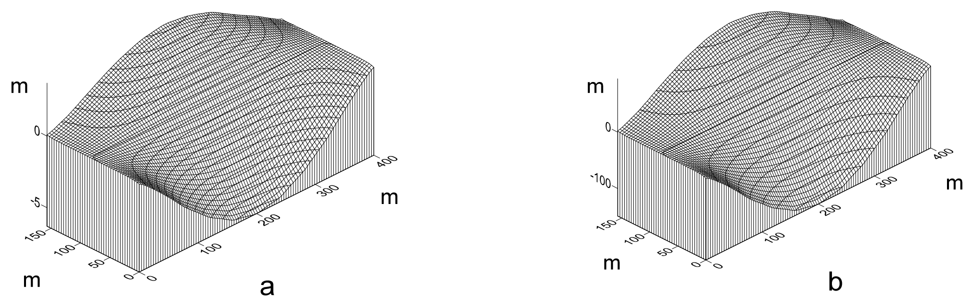

Fig. 4. Landslide deforming of anticline geostructures, which consist of soft dispersing grounds, under gravity forces action:
a – semi rigid grounds; b – tight plastic grounds

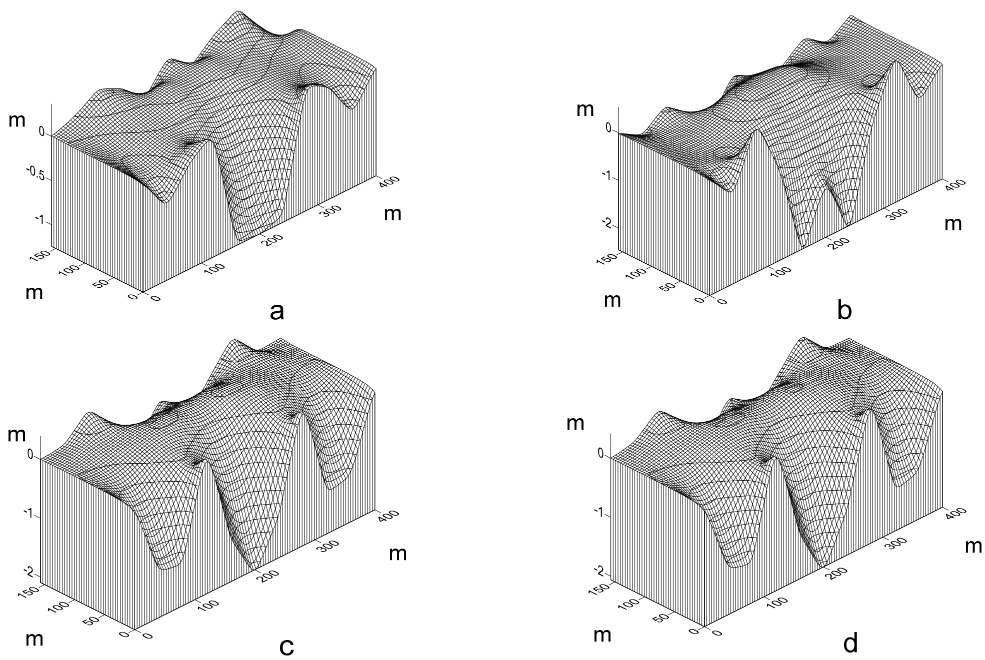

Fig. 5. Landslide deforming of three layers anticline geostructures with thickness of 10 m, which consist of combination of different dispersing grounds, under gravity forces action (calculation of layers begins from the bottom):
a – rigid, semi rigid, tight plastic; b – rigid, semi rigid, plastic; c – rigid, semi rigid, soft plastic; d – rigid, semi rigid, fluent plastic

Discussion of the results. The modeling results show that the shear deformation of anticlinal geostructures under the influence of gravity depends on the size of the structure, its shape and the mechanical properties of the rocks that make up these structures and, in some cases, requires careful research. In the fig. 1, we can reveal the degree of intensity of shear deformation of anticlinal geostructures of different linear sizes, consisting of the solid rocks. We can see that more compact structures are subject to the smallest deformation (Fig. 1a), for example, in a geostructure with a linear size of 300 m, the amplitude of the landslide does not exceed 7 cm, as the linear dimensions increase, the degree of deformation increases in a non-linear way. Thus, in the geostructure extending for 700 m (Fig. 1d), the amplitude of the landslide reaches 2.5 m. The largest shear deformations are observed in the lower middle part of the anticlinal geostructure, they have negative values (as the movement is clockwise), deformations in the positive direction can be observed in the upper part of the geostructure. This means that under the influence of gravity, the top of the geostructure can shift in the opposite angular direction. The fig. 2. presents the shear deformation of anticlinal geostructures, which consist of solid dispersed soil rocks (clays, sands, loams, sandy loams, etc.). These rocks have a rigidity approximately 10 times lower than a solid rock. As these rocks completely save their elastic properties, the inversely proportional character of the deformation relative to the rigidity of the rocks obviously will take place. So, we can see that in the fig. 2 magnitudes of deformations are approximately 10 times higher than the deformations of rock geostructures of corresponding sizes in the fig. 1. The fig. 3 presents the nature of shear deformation of anticlinal geostructures with a radius of curvature 20 percent smaller than the geostructures considered in the fig. 2. We can see that in this case, in comparison with the previous geostructures, which have the corresponding linear dimensions (Fig. 2a, b), shear deformations also increase by approximately 20 percent. Thus, in solid geostructures, where elastic properties are preserved, a decreasing of the radius of the geostructure leads to an inversely proportional increasing of the degree of deformation of the corresponding geostructure. In the fig. 4 there are presented shear deformation of anticlinal geostructures consisting of semi-hard and rigid-plastic dispersed soil rocks. We can see by comparing (Fig. 4a, b) that if elastic properties and corresponding deformations are still preserved for the semi-solid geostructures, but for the rigid-plastic geostructures there is a sharp jump in plastic creep, which leads to the complete destruction of the corresponding geostructure. Thus, we can conclude that in order to maintain resistance to gravitational destruction, anticlinal geostructures cannot consist entirely of rocks softer than semi-solid dispersed soils. Fig. 5 presents the nature of shear deformation of three-layer anticlinal geostructures, which consist of combinations of: solid, semi-solid, rigid, plastic, soft-plastic, and fluid-plastic dispersed soil rocks. Based on the previous results about the stability of anticlinal geostructures under the gravity load, we can suggest that only those structures can really exist where the lower and middle layers consist of solid and semi-solid dispersed soils, respectively. Comparing the cases (Fig. 4a-d), where the upper layers consist of rigid plastic, plastic, soft plastic and fluid plastic dispersed soils, we can see the nonlinear character of the shear deformation of these geostructures depending on the stiffness of the specified rocks. Indeed, at first, we can see an increasing of the amplitude of landslides in the case of the upper rigid plastic and plastic soils, but then in the upper soft plastic and liquefiable soils we observe a slight but decreasing of the corresponding amplitudes of the landslides. Thus, the following conclusions can be made. Firstly, the gravitational shear deformation and resistance to the failure of multi-layered anticlinal geostructures is mainly determined by the rigidity of the internal bearing rocks, while the influence of the rigidity of the external rocks is relatively insignificant. Secondly, the stiffness of external soft soil rocks affects the shear deformation of multi-layered anticlinal geostructures in a non-linear way. This can be explained by the fact that in the defined intervals of nonlinearity, soft dispersed soils are more capable of strengthening and corresponding coupling under gravity load conditions.

Conclusions. The developed variational finite-element method for solving the elasticity problem for multi-layer orthotropic shells of rotation taking into account the shear rigidity allows to adequately investigate the shear rotational deformations and destructions criterions of heterogeneous three-dimensional anticlinal geostructures under the gravity load conditions at a quantitative level. The modeling results show that the shear deforming of anticlinal geostructures under the influence of gravity depends on the shape, dimensions of the structure, and mechanical properties of the soil rocks that make up these geostructures. It was established that more compact geostructures are subjected to the smallest shear deformation. In the solid geostructures that retain elastic properties, the shear deformation is inversely proportional to the degree of the rock stiffness, and a decreasing in the curvature radius of the geostructure leads to an inversely proportional increasing in the shear deforming of the corresponding geostructure. We have shown that in order to maintain resistance to gravitational shear failure, anticlinal geostructures cannot be completely composed of rocks softer than semi-solid dispersed soils. It was established that the resistance to gravitational destruction of heterogeneous anticlinal geostructures is mainly determined by the rigidity of the internal bearing rocks, while the influence of the stiffness of the external soft rocks is relatively insignificant and have a non-linear behavior. In the future, it is interesting to create a practically significant methodology for the prediction of natural and man-made gravitational shear solid failures based on the developed variational finite-element method.

References

Bell, F., Maud, R.R. (2000). Landslide associated with the colluvial soils overluing the Natal group in the greater Durban region of Natal, South Africa. *Environmental geology*, 39 (9), 1029–1038.

Dikau, R., Brunsder, P., Schrott, L., Ibsen, M.L. (1996). Landslide recognition. Wiley: Chichester, U.K.

Fomenko, I.K. (2012). Modern tendencies in calculations of the slopes stability. *Engeineering geology,* 6, 44–53. [in Russian]

Grigorenko, A.G., Kyuntsel, V.V., Novak, V.E., Tamutis, Z.P. (1992). Engineering geodynamics: textbook for higher education. Kyiv: Lubid. [in Russian]

Hunter, G., Fell, R. (2003). Travel distance angle for "rapid" landslides in constructed and natural soil slopes. *Canadian geotechnical journal*, 40, 1123–1141.

Lubkov, M.V. (2015). Forming process of the large scale geostructures in zone of continents collision. *Geoinformatics*, 54 (2), 38–45. [in Ukrainian]

Niyazov, R.A. (2015). Landslides, called by Pamir-Gindukus earthquake. Taskent: GP "Institute GIDROENERGO". [in Russian]

Osipov, V.I. (1999). Dangerous exogenous processes. Moscow: GEOS. [in Russian]

Pathak, D.R., Gharti, H.N., Singh, A.B., Hiratsuka A. (2008). Stochastic modeling of progressive failure in heterogeneous soil slope. *Geotechnical and geological engineering*, 26, 113–120.

Pendin, V.V., Fomenko, I.K. (2015). Metodology of evaluation and prognosis of landslide danger. Moscow: LENAND. [in Russian]

Trofimov, V.T. (2005). Soil science. Moscow: NAUKA. [in Russian]

Van Asch, T., Van Beek, L., Boggart, T. (2007). Problems in predicting the mobility of slow-moving landslides. *Engineering geology*, 91, 46–55.

Vay, Y.C. (2010). The main characteristics of the Vanchyang earthquake and its influence on the dangerous geological processes. *Georisk,* 1, 10–14. [in Russian]
Zhang, W.G., Chen, Y.M., Zhan, L.T. (2006). Loading/unloading response ratio theory applied in predicting deep-seated landslides triggering. *Engineering geology*, 82, 234–240.
Kyul, E.V. (2017). Tectonic landslide massifs of the Central Caucasus. *Geology and geophysics of the South Russia,* 2, 67–81. [in Russian]
Cruden, D., Lan Heng-Xing. (2015). Using the working classification of landslides to asses the danger from a natural slope. *Engineering geology for society and territory,* 2, 3–12.

Список використаних джерел
Вэй, Ю.Ц. (2010). Основные характеристики Вэнчуаньского землетрясения и его влияние на опасные геологические процессы. *Георкиск,* 1, 10–14.
Григоренко, А.Г., Кюнтцель, В.В., Новак, В.Е., Тамутис, З.П. (1992) Инженерная геодинамика: учеб. пособие. К: Лыбидь.
Кюль, Е.В. (2017). Тектонические оползневые массивы Центрального Кавказа. *Геология и геофизика Юга России,* 2, 67–81.
Лубков, М.В. (2015). Процес формування великомасштабних геоструктур в зоні колізії континентів. *Геоінформатика,* 54 (2), 38–45.
Ниязов, Р.А. (2015). Оползни, вызванные Памиро-Гиндукушским землетрясением. Ташкент: ГП "Институт ГИДРОИНГЕО".
Осипов, В.И. (1999). Опасные экзогенные процессы. М.: ГЕОС.
Пендин, В.В., Фоменко, И.К. (2015). Методология оценки и прогноза оползневой опасности. М.: ЛЕНАНД.
Трофимов, В.Т. (2005). Грунтоведение. М.: Наука.
Фоменко, И.К. (2012). Современные тенденции в расчетах устойчивости склонов. *Инженерная геология,* 6, 44–53.
Bell, F., Maud, R.R. (2000). Landslide associated with the colluvial soils overluing the Natal group in the greater Durban region of Natal, South Africa. *Environmental geology*, 39 (9), 1029–1038.
Cruden, D., Lan Heng-Xing. (2015). Using the working classification of landslides to asses the danger from a natural slope. *Engineering geology for society and territory,* 2, 3–12.
Dikau, R., Brunsder, P., Schrott, L., Ibsen, M.L. (1996). Landslide recognition. Wiley: Chichester, U.K.
Hunter, G., Fell, R. (2003). Travel distance angle for "rapid" landslides in constructed and natural soil slopes. *Canadian geotechnical journal*, 40, 1123–1141.
Pathak, D.R., Gharti, H.N., Singh, A.B., Hiratsuka A. (2008). Stochastic modeling of progressive failure in heterogeneous soil slope. *Geotechnical and geological engineering*, 26, 113–120.
Van Asch, T., Van Beek, L., Boggart, T. (2007). Problems in predicting the mobility of slow-moving landslides. *Engineering geology*, 91, 46–55.
Zhang, W.G., Chen, Y.M., Zhan, L.T. (2006). Loading/unloading response ratio theory applied in predicting deep-seated landslides triggering. *Engineering geology*, 82, 234–240.

Надійшла до редколегії 01.12.22

М. Лубков, д-р фіз.-мат. наук, ст. наук. співроб.
e-mail: mikhail.lubkov@ukr.net
Полтавська гравіметрична обсерваторія Інституту геофізики ім. С.І. Субботіна НАНУ,
вул. Мясоєдова, 27/29, м. Полтава, 36014, Україна

МОДЕЛЮВАННЯ ЗСУВНИХ ДЕФОРМАЦІЙ ПІД ДІЄЮ СИЛИ ТЯЖІННЯ

На сьогодні актуальними залишаються проблеми, пов'язані з деструктивними схиловими процесами під дією гравітаційного навантаження. Дійсно, гравітаційні схилові процеси разом з іншими ерозійно-тектонічними процесами мають значний вплив на формування сучасного рельєфу і водночас дуже часто ускладнюють раціональне використання відповідної території. Серед найнебезпечніших гравітаційних схилових процесів можна виділити оповзневі (зсувні) процеси. Ці процеси характеризуються значним поширенням, матеріальними втратами та людськими жертвами. Проблеми вивчення процесів гравітаційного зсуву через свою соціальну важливість та практичну інженерну значущість мають давню історію. Відповідно цим проблемам присвячено багато робіт, але, з іншого боку, випадки строгого математичного й механічного опису та визначення певних кількісних механізмів і критеріїв щодо розвитку зсувних гравітаційних процесів розглядалися досить обмежено.

У представленій роботі на основі варіаційного методу скінченних елементів розраховано кількісні критерії обертального деформування та руйнування широкого класу тривимірних неоднорідних антиклінальних геоструктур в умовах гравітаційного навантаження. Результати моделювання показують, що зсувні деформації антиклінальних геоструктур під дією сили тяжіння залежать від форми, розмірів структури та механічних властивостей гірських порід, які утворюють ці геоструктури. Встановлено, що найменшим деформуванням піддаються більш компактні геоструктури. У твердих геоструктурах, що зберігають пружні властивості, амплітуди деформацій є обернено пропорційними ступеню жорсткості порід, а зменшення радіуса кривизни геоструктури призводить до обернено пропорційного збільшення деформування відповідної геоструктури. Ми показали, що для здатності збереження стійкості щодо руйнування під дією сили тяжіння, антиклінальні геоструктури не можуть повністю складатися з порід, м'якших за напівтверді дисперсні ґрунти. Встановлено, що стійкість до зсувно-гравітаційного руйнування неоднорідних антиклінальних геоструктур в основному визначається жорсткістю внутрішніх несучих порід, тоді як вплив жорсткості зовнішніх м'яких порід є відносно незначним і нелінійним.

Ключові слова: комп'ютерне моделювання, оповзневі деформації антикліналей, гравітаційне навантаження.