UDC 551.2.3

Myhailo LUBKOV*

Poltava Gravimetric Observatory of Subbotin Institute of Geophysics of NAS of Ukraine, 27/29, G. Myasoedova str., Poltava, 36004, Ukraine, e-mail: Mikhail.lubkov@ukr.net,0955395389, https://orcid.org/0009-0009-2440-9824.

https://doi.org/10.23939/jgd2025.01.049

LANDSLIDE PROCESSES IN THE ASYMMETRIC ANTICLINE GEOSTRUCTURES

The purpose of the research is to explore both the theoretical and practical aspects of natural and man-made gravitational shear deformations and fractures. This will be based on the variational finite element method used to solve elasticity problems for asymmetric multilayer orthotropic shells of rotation while accounting for shear stiffness. To achieve this, we have modeled the shear deformations and failures of heterogeneous three-dimensional asymmetric anticline geostructures under the influence of gravity using the method mentioned above. The method of research. The research employs the variational finite-element method to address the elasticity of multilayer orthotropic shells of rotation, with particular attention to shear stiffness. This approach enables us to accurately assess the degree of deformation and the criteria for the failure of asymmetric three-dimensional heterogeneous anticline geostructures under gravitational forces. This method holds significant theoretical and practical interest. The main result of this study is the establishment of patterns in the shear deformation of asymmetric anticline geostructures under the influence of gravity. The findings indicate that the amplitudes of shear deformation are affected by the degree of asymmetry, the dimensions of the structure, and the mechanical properties of the rocks that compose these geostructures. In solid geostructures that maintain elastic properties, the deformations are inversely proportional to the stiffness of the surrounding rocks. A decrease in the radius of the geostructure results in a reduction of the corresponding deformation. Conversely, an increase in the linear dimensions of the geostructure leads to greater deformation amplitudes. Moreover, the presence of a non-rigid outer layer significantly impacts how the shape asymmetry of anticline geostructures affects their shear deformation. This asymmetry can result in critical quantitative and qualitative changes, potentially destroying the geostructure. The scientific novelty of this research is the establishment of quantitative regularities regarding the shear deformation of the asymmetric anticline geostructures under gravity. We demonstrate that a decrease in the radius of a geostructure results in a reduction of deformation in that structure. Conversely, an increase in the linear dimensions of the geostructure leads to greater deformation. Additionally, a non-rigid outer layer significantly affects the shear deformation of asymmetric anticline geostructures due to the shape's asymmetry. The practical significance of this work lies in the ability to use quantitative estimates to predict and minimize destructive shear processes in asymmetric anticline geostructures under the influence of gravity.

K*ey words:* computer modeling, solving the problem of the layered shells elasticity, gravitational landslides of the heterogeneous asymmetric anticline geostructures.

Introduction

Nowadays the issues related to destructive slope processes caused by gravitational forces are relevant. Gravitational slope processes, along with other external and tectonic events, play a significant role in shaping modern terrain. Unfortunately, these processes frequently complicate the effective use of the affected areas. Landslides are among the most hazardous gravitational slope events. These events are characterized by their widespread occurrence, significant material losses, and potential human casualties. Landslide processses are characterized by soil shifting without losing continuous contact between the moving and stationary parts of the massif [Grigorenko etc., 1992; Osipov, 1999]. Thus, we can describe gravitational shear soil processes by neglecting gaps within the soil mass and other rheological effects. Therefore, we can focus on applying the theory of elasticity as it relates to a solid medium. 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, for instance [Vej, 2010; Kjul', 2017; Nijazov, 2015; Pendin, 2015; Fomenko, 2012; Gruden & Lan Heng-King, 2015; Dikau et al., 1996; Jaboyedoff et al., 2013; Troiani et al., 2020]. 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.

On the other hand, the cases involving strict mathematical and mechanical descriptions, as well as the determination of specific quantitative mechanisms and criteria for the development of sliding gravity processes–particularly concerning rheological numerical methods–have been explored only to a limited extent.

This paper proposes a variational finite-element method to address the elasticity of multilayer orthotropic shells, taking shear rigidity into account [Kozlov et al., 1995; Lubkov, 2015]. This method enables accurate calculations of deformation processes, mechanical behavior, and failure criteria for a specific class of three-dimensional asymmetric anticlinal geostructures under gravitational loads. This approach holds significant theoretical and practical interest and offers several advantages over existing methods.

Formulation of the problem

Consider the deformation of the anticlinal geostructure that resembles the upper half of a fragment of a three-layer cylindrical or conic shell, which is rigidly fixed at the ends and subjected to the force of gravity. To analyze the deformation of the anticlinal geostructure, which consists of rocky or dispersed soil rocks [Trofimov, 2005] we will employ the theory of multilayer orthotropic elastic shells of rotation taking shear rigidity into account [Kozlov etc., 1995; Lubkov, 2015]. We will consider the shell in the curvilinear coordinate system (s, φ, z), which is rigidly fixed with a large solid rock massif. Here s, φ are 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 [Kozlov etc., 1995; Lubkov, 2015]:

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

here u_0, v_0, w_0 are displacement components of the middle surface of the shell; u_1, v_1 are rotation angles of the middle surface normal relative to coordinate lines φ = const, s = const accordingly, w_1 is compression of the middle surface normal of the shell. Let us make the Lagrange functional [Kozlov etc., 1995; Lubkov, 2015], which expresses the potential mechanical energy of the considered geostructure under gravitational load conditions:

$$W = \frac{1}{2}\sum_{j=1}^{3}\iiint_{h_j S}[E_{ss}^{j}\varepsilon_{ss}^{j2} + E_{\varphi\varphi}^{j}\varepsilon_{\varphi\varphi}^{j2} + E_{zz}^{j}\varepsilon_{zz}^{j2} + 2E_{s\varphi}^{j}\varepsilon_{ss}^{j}\varepsilon_{\varphi\varphi}^{j} + 2E_{sz}^{j}\varepsilon_{ss}^{j}\varepsilon_{zz}^{j} + 2E_{\varphi z}^{j}\varepsilon_{\varphi\varphi}^{j}\varepsilon_{zz}^{j} + 4G_{s\varphi}^{j}\varepsilon_{s\varphi}^{j2} + 4G_{sz}^{j}\varepsilon_{sz}^{j2} + 4G_{\varphi z}^{j}\varepsilon_{\varphi z}^{j2} - 2\rho_j g w_j](1+\frac{z}{R_1})(1+\frac{z}{R_2}) \times$$
$$\times\, ds\,d\varphi\,dz - \oint_{\varphi_1}^{\varphi_2}(T_s u_0 + T_{s\varphi} v_0 + Q_s w_0)d\varphi -$$
$$- \oint_{s_1}^{s_2}(T_{\varphi s} u_0 + T_{\varphi} v_0 + Q_{\varphi} w_0)ds \qquad (2)$$

here R_1, R_2 are the radiuses of curvature on the left and right ends of the geostructure; g is gravity aceleration; S is the surface area of the geostructure; h_j is the thickness of the j-th layer of rocks of the geostructure; ρ_j is the density of the j-th layer; $\varepsilon_{\alpha\beta}^{j}$ are components of the strain tensor of the j-th layer; $E_{\alpha\beta}^{j}$ is the modulus of elasticity of the j-th layer; $G_{\alpha\beta}^{j}$ are components of the shear modulus of the j-th layer; $T_{\alpha}, T_{\alpha\beta}$ are forces acting on the contour of the geostructure in the tangential directions to its surface; Q_{α} are 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. Suppose the beginning of the coordinate system is taken to be the left end of the considered fragment of the geostructure, which has the form of the upper half of a three-layer conical shell. The length of the shell is taken as *L*. In this case, the boundary conditions of the problem have the form:

$$u_0(s=0)=0, v_0(s=0)=0, w_0(s=0)=0;$$
$$u_0(s=L)=0, v_0(s=L)=0, w_0(s=L)=0. \qquad (3)$$

Method of the problem-solving

To address the issue of the geostructure deformation caused by gravity, we will utilize the finite element method, which is based on Lagrange's variational principle. This principle indicates the minimization of the system's potential mechanical energy [Kozlov etc., 1995; Lubkov, 2015; Zienkiewicz & Taylor, 2005]:

$$\delta \text{Э}(u_0, v_0, w_0, u_1, v_1, w_1) = 0 . \qquad (4)$$

For solving the variational equation (4), we use the nine-node isoparametric quadrilateral shell finite element with a curved surface [Kozlov, etc., 1995; Lubkov, 2015]. A curvilinear coordinate system (s, φ, z) is used as a global one, i.e. a system where all finite elements (on which the research area is divided) are combined. A normalized coordinate system (ξ, θ) is used as a local one, where every finite element form function is constructed. To create finite element shape functions that approximate displacement components within each element $u_0, v_0, w_0, u_1, v_1, w_1$, we utilize algebraic and trigonometric polynomials to ensure smoothness and convergence of the finite element solution [Kozlov, etc., 1995; Lubkov, 2015]:

$$u_0 = \sum_{i=1}^{9} N_i u_{0i};\; v_0 = \sum_{i=1}^{9} N_i v_{0i};\; w_0 = \sum_{i=1}^{9} N_i w_{0i};$$

$$u_1 = \sum_{i=1}^{9} N_i u_{1i};\; v_1 = \sum_{i=1}^{9} N_i v_{1i};\; w_1 = \sum_{i=1}^{9} N_i w_{1i} \qquad (5)$$

$$N_1 = H_1(\theta)P_1(\xi);\; N_2 = H_1(\theta)P_2(\xi);$$
$$N_3 = H_3(\theta)P_2(\xi);\; N_4 = H_3(\theta)P_1(\xi);$$
$$N_5 = H_1(\theta)P_3(\xi);$$
$$N_6 = H_2(\theta)P_2(\xi);\; N_7 = H_3(\theta)P_3(\xi);$$
$$N_8 = H_2(\theta)P_1(\xi);\; N_9 = H_2(\theta)P_3(\xi). \qquad (6)$$

$$H_1(\theta) = \frac{\sin(\theta - \theta_2) - \sin(\theta - \theta_3) + \sin(\theta_2 - \theta_3)}{\sin(\theta_1 - \theta_2) - \sin(\theta_1 - \theta_3) + \sin(\theta_2 - \theta_3)};$$

$$H_2(\theta) = \frac{\sin(\theta - \theta_3) - \sin(\theta - \theta_1) + \sin(\theta_3 - \theta_1)}{\sin(\theta_2 - \theta_3) - \sin(\theta_2 - \theta_1) + \sin(\theta_3 - \theta_1)};$$

$$H_3(\theta) = \frac{\sin(\theta - \theta_1) - \sin(\theta - \theta_2) + \sin(\theta_1 - \theta_2)}{\sin(\theta_3 - \theta_1) - \sin(\theta_3 - \theta_2) + \sin(\theta_1 - \theta_2)};$$

$$H_j(\theta_k) = \begin{cases} 1, & j = 1 \\ 0, & j \neq 1 \end{cases};$$

$$P_1(\xi) = \frac{1}{2}\xi(\xi - 1);\; P_2(\xi) = \frac{1}{2}\xi(\xi + 1);$$

$$P_3(\xi) = 1 - \xi^2. \qquad (7)$$

The finite-element algorithm for solving the variational problem (4) is the following. In the initial stage, within the local coordinate system (ξ, θ), we approximate all displacements and deformations from functional (2). These are functions of the displacement components $u_0, v_0, w_0, u_1, v_1, w_1$, achieved through formulas (5)–(7). In our local system, we perform analytical integration within each shell layer and then sum the results across them all. In the second stage, we vary the functional (2) relative to all nodal displacement components and set the corresponding variations equal to zero. This process yields a linear algebraic system of 54 equations for each finite element. We summate the local linear systems of algebraic equations across all the finite elements that make up the shell in the global coordinate system (s, φ, z). We also establish the formation of the global system of linear equations. We calculate double integrals over the area of the shell through numerical integration using Gauss's quadrature formulas [Kozlov etc., 1995; Lubkov, 2015]. We resolve the global system of linear algebraic equations using the Gauss numerical method [Kozlov etc., 1995; Lubkov, 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. Displacements, deformations, stresses, and other relevant values can be determined from the calculated nodal displacement components at any point within the finite element, specifically at any location of the analyzed shell geostructure.

Modeling the landslide deformation of the asymmetric anticline geostructures

When modeling the gravitational shear processes of asymmetric anticline geostructures, we will analyze the deformation of the upper half of a three-layer cylindrical shell subjected to gravity. The parameters for this model are as follows: the radius of the left end of the shell is 100 meters, while the radius of the right end varies. *(5)* Each of the three shell layers has a thickness of 10 meters. The angle from the horizontal in the positive direction (counter-clockwise) is $\pi / 2$. The average density of the rocks under consideration is assumed to be 2,300 kg/m^3. Firstly, we will examine the shear deformation (movement in the angular direction), along the slope of homogeneous anticlinal geostructures. In Fig. 1, we analyze the case of rocks [Trofimov, 2005] with the following elastic properties: Young's modulus E = 7×10^{10} Pa, Poisson's ratio μ = 0.3. The length of this geostructure is 400 m. Fig. 2 depicts rocky asymmetric anticlinal geostructures with a length of 600 m. Fig. 3 shows the gravity deformation of asymmetric anticlinal geostructures, which consist of solid dispersed rocks (E = 7×10^9 Pa, μ = 0.3) and semi-solid dispersed soil rocks (E = 2×10^9 Pa, μ = 0.35) with the length of 600 m. Fig. 4 shows the deformation of asymmetric multilayer geostructures composed of the intrinsic rocky layer, the middle solid dispersed soil rocks layer, and the outer tough-plastic dispersed soil rocks (E = 10^8 Pa, μ = 0.4) layer [Trofimov, 2005] and with the length of geostructure of 600 m.

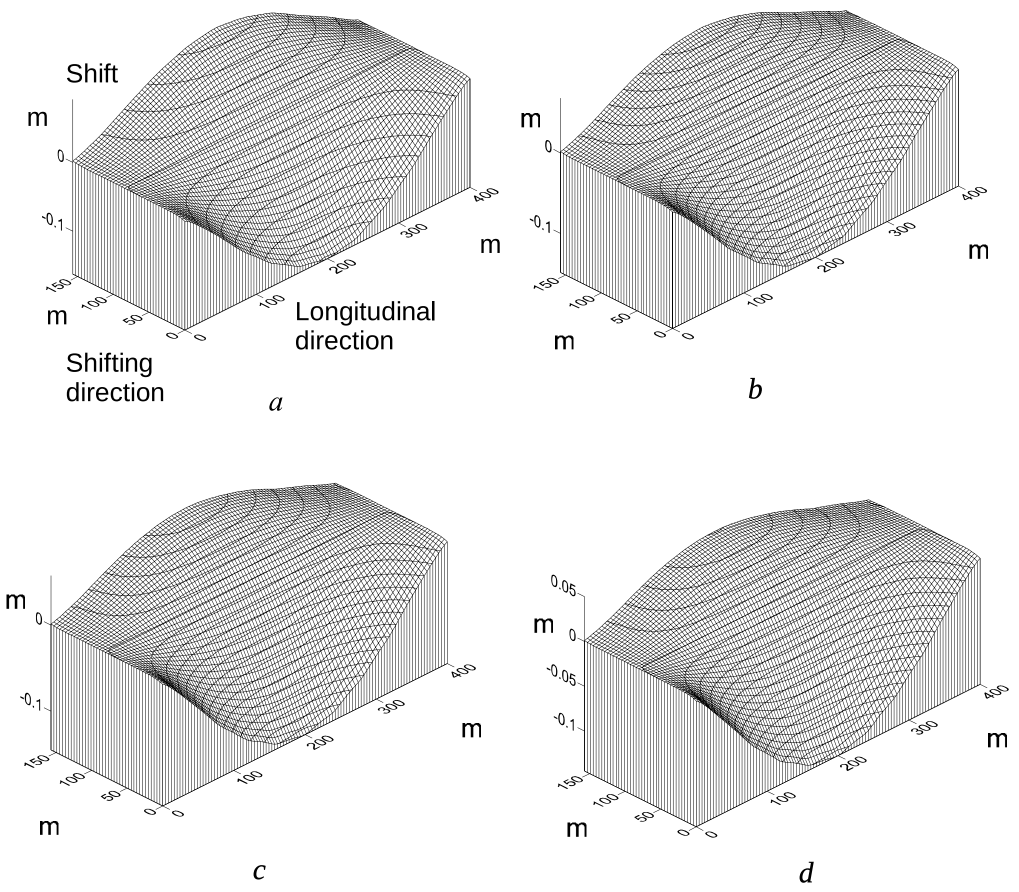


Fig. 1. Landslide shifting of anticline geostructures, which consist of rigid rocks,
under gravity forces action in the angle direction:

a – cylindrical geostructure with both radiuses 100 m; b – conic geostructure with the left radius 100 m and right radius 70 m; c – conic geostructure with the left radius 100 m and right radius 50 m; d – conic geostructure with the left radius 100 m and right radius 30 m.

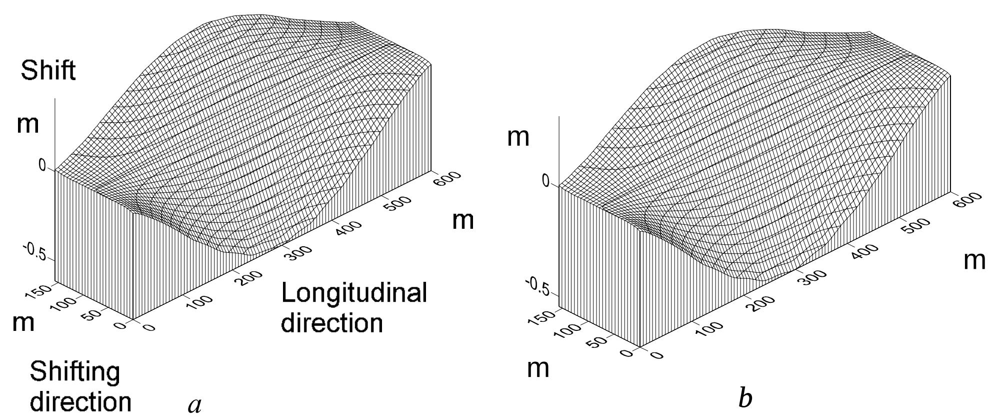
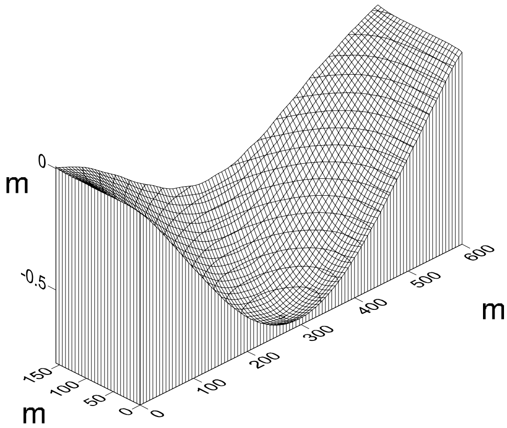
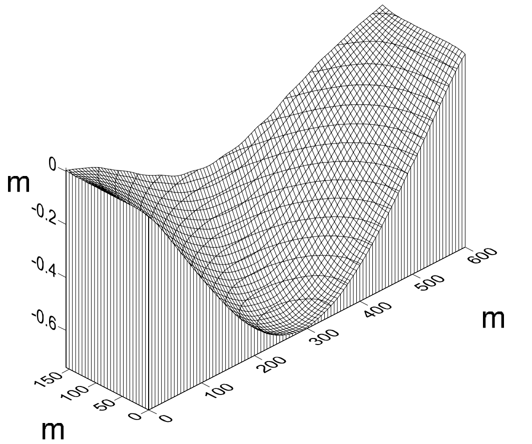


Fig. 2. Landslide shift of conic anticline geostructures, which consist of rigid rocks,
under gravity forces action:

a – in the angle direction, left radius is 100 m, right – 70 m;
b – in the angle direction, left radius is 100 m, right – 50 m.



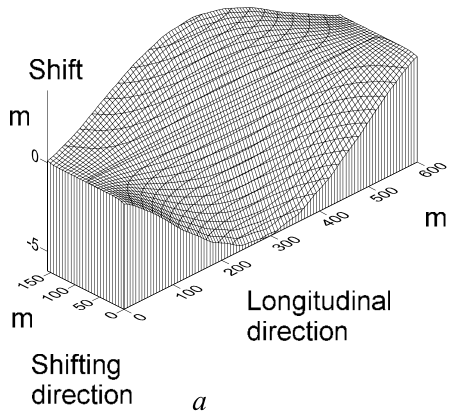
c



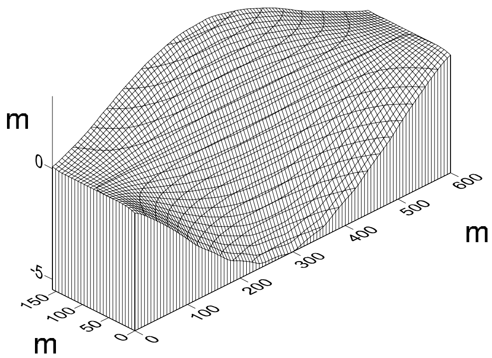
d

Fig. 2. (Continuation). Landslide shift of conic anticline geostructures, which consist of rigid rocks, under gravity forces action:

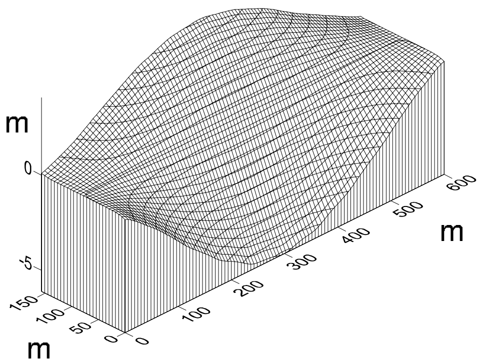
c – in the vertical direction, left radius is 100 m, right – 70 m;
d – in the vertical direction, left radius is 100 m, right – 50 m.



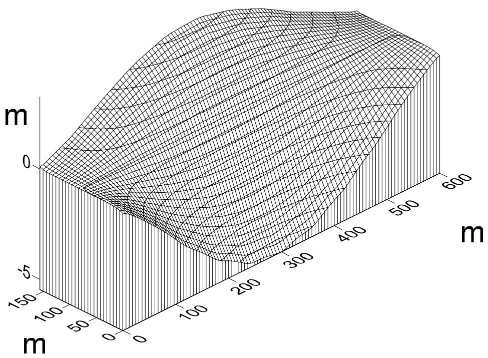
a



b



c



d

Fig. 3. Landslide shift of conic anticline geostructures in the angle direction, which consist of rigid dispersed rocks, under gravity forces action:

a – left radius is 100 m, right – 70 m; b – left radius is 100 m, right – 50 m. And semi-solid dispersed soil rocks:
c – left radius is 100 m, right – 70 m; d – left radius is 100 m, right – 50 m.

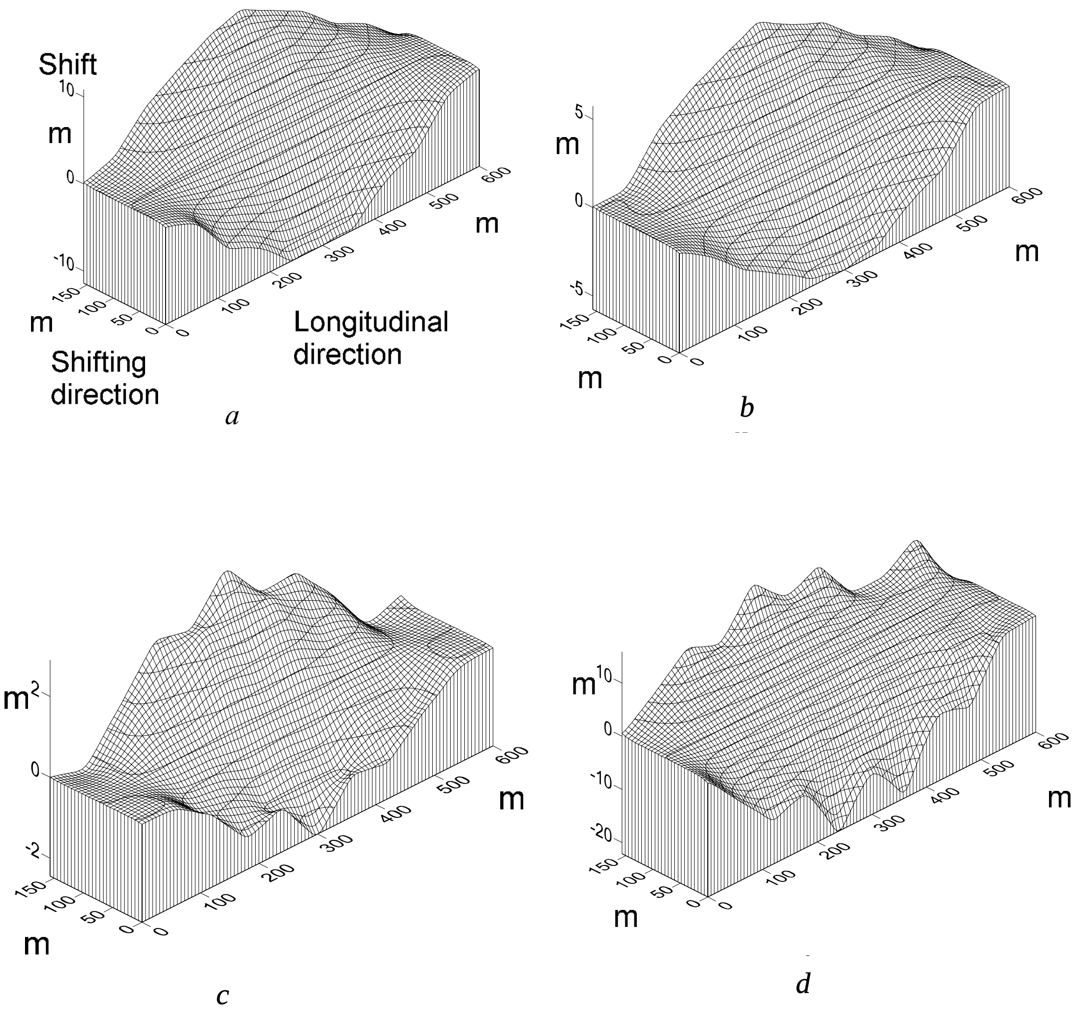


Fig. 4. Landslide shift of multilayer conic anticline geostructures in the angle direction, composed of the intrinsic rocky layer, the middle solid dispersed soil rocks layer, and outer tough-plastic dispersed soil rocks, under gravity forces action:

a – left radius is 100 m, right – 80 m; b – left radius is 100 m, right – 70 m;
c – left radius is 100 m, right – 60 m; d – left radius is 100 m, right – 50 m.

Analysis of the results

The modeling results indicate that the shear deformation of anticlinal asymmetric geostructures, influenced by gravity, depends on several factors: the size of the structure, the degree of asymmetry, and the mechanical properties of the rocks that compose these structures. In some cases, this requires careful examination. In Fig. 1, we illustrate the intensity of shear deformation in anticlinal geostructures consisting of solid rocks as this relates to the degree of asymmetry. It is observed that shear deformation increases slightly as the radii of the left and right parts of the geostructure become equal. 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. Fig. 2 illustrates the shear deformation of conical anticlinal geostructures composed of rocks with increased linear dimensions.

An increase in the linear dimensions of these geostructures leads to a corresponding growth in their shear deformation. Moreover, the deformation in the angular direction is correlated with the one in the vertical direction. Fig. 3 presents the characteristics of shear deformation in conical anticlinal geostructures made up of solid and semi-solid dispersed soils. Compared to the rocks, the amplitudes of shear deformations in solid dispersed soils increase by approximately ten times. This significant increase is consistent with a similar reduction in the rigidity of the solid dispersed rocks, confirming their elastic behavior. At that time, the difference in shear deformation between geostructures consisting of solid and semi-solid dispersed rocks is insignificant. Fig. 4 illustrates the deformation of asymmetric multilayer geostructures composed of the intrinsic rocky layer, a middle layer of solid dispersed soil rocks, and an outer layer of tough-plastic dispersed soil rocks. Comparing Figs. 4, *a*, *b*, *c* and *d*, it becomes evident that even slight changes in the symmetry of the left and right ends of the conical geostructures can lead to significant quantitative and qualitative alterations in their shear deformations. Therefore, to ensure resistance to gravitational collapse, layered asymmetric anticlinal geostructures should be primarily composed of rocky or hard dispersed rocks, particularly in the internal bearing layers. They should maintain minimal symmetrical differences. Thus, we can make the following conclusions. First, the gravitational shear deformation and resistance to destruction of the multilayered asymmetric anticlinal geostructures is mainly determined by the rigidity of the internal bearing rocks. Secondly, the presence of the non-rigid outer layers significantly influences the asymmetry of anticlinal geostructures during shear deformation. The variational finite element method discussed here addresses the elasticity problem for multilayered orthotropic shells of rotation, taking shear rigidity into account. This approach allows for a thorough quantitative investigation of shear deformation and failure in heterogeneous, asymmetric three-dimensional anticlinal geostructures under gravitational loading. This approach has advantages over other methods in this field of research, which primarily focus on general geological and engineering classifications, qualitative criteria, and the mechanisms of destructive events. In the future, we plan to expand this method for use in a broader range of heterogeneous anticlinal geostructures.

Conclusions

The variational finite-element method developed for addressing elasticity problems in multilayer orthotropic shells of rotation takes shear rigidity into account. This approach enables the examination of shear deformation and failure behavior in heterogeneous, asymmetric, three-dimensional anticlinal geostructures subjected to gravitational forces. It provides valuable quantitative insights, which is a significant advantage over other methods in this research area. Many existing methods mainly focus on defining general geological and engineering classifycations along with qualitative criteria and mechanisms related to destructive events. The modeling results show that shear deformation in asymmetric anticlinal geostructures, due to gravity, is influenced by their degree of asymmetry, linear dimensions, and the mechanical properties of the constituent rocks. It was found that more compact geostructures experience less shear deformation. In predominantly solid geostructures that retain the elastic properties of the rocks, there is an inversely proportional relationship between shear deformation and the rigidity of the rocks. We have demonstrated that the deformation caused by gravitational landslides and the resistance to the destruction of multi-layered asymmetric anticlinal geostructures are primarily determined by the rigidity of the internal bearing rocks. The presence of the non-rigid outer layers significantly affects how the asymmetry of anticlinal geostructures influences their shear deformation process under the force of gravity. This can result in critical changes, both quantitative and qualitative, potentially leading to the destruction of such geostructures.

References

Cruden, D., & Lan Heng-Xing (2015). Using the working classification of landslides to assess the danger from a natural slope. *Engineering geology for society and territory, 2,* 3–12. https://doi.org/10.1007/978-3-319-09057-3_1

Dikau, R., Brunsder, P., Schrott, L., & Ibsen, M. L. (1996). Landslide recognition. Wiley: Chichester, U. K., 1996, 251 p.

Fomenko, I. K. (2012). Modern trends in slope stability calculations. *Engineering geology*, 6, 44–53 (in Russian).

Grigorenko, A. G., Kjuntcel’, V. V., Novak, V. E., & Tamutis, Z. P. (1992). *Engineering geodynamics*: textbook. K: Libid’, 296 p. (in Russian)

Jaboyedoff, M., Penna, I., Pedrazzini, A., Baroň, I., & Crosta, G. B. (2013). An introductory review on gravitational-deformation induced structures, fabrics and modeling. *Tectonophysics*, *605*, 1–12. https://doi.org/10.1016/j.tecto.2013.06.027

Kozlov, V. I., Lubkov, M. V. (1990). Vibrations of multilayer orthotropic shells of revolution with finite shear rigidity. Proceedings of the 15th scientific conference of young scientists of the Institute of Mechanics of the Academy of Sciences of the Ukrainian SSR, Kyiv, N 3802-B 90, pp. 439–445 (in Russian).

Kjul', E. V. (2017). Tectonic landslide massifs of the Central Caucasus. Geology and geophysics of the South of Russia. *7*(2), 67–81 (in Russian)

Lubkov, M. V. (2015). Prosess of large scale geostructures forming in the continental collision zone. *Geoinformatika,* 2, 38–45 (in Ukrainian). http://dspace.nbuv.gov.ua/handle/123456789/125343

Nijazov, R. A. (2015). Landslides caused by the Pamir-Hindu Kush earthquake. Tashkent: GP "Institut GIDROINGEO", 224 p. (in Russian).

Osipov, V. I. (1999). Dangerous exogenous processes. M.: GEOS, 1999. 290 s. (in Russian).

Pendin, V. V., & Fomenko, I. K. (2015). Methodology for assessing and predicting landslide hazard. M., 320 p. (in Russian).

Trofimov, V. T. (2005). Soil science. M.: Nauka, 1023 p. (in Russian).

Troiani, F., Martino, S., Marmoni, G. M., Menichetti, M., Torre, D., Iacobucci, G., & Piacentini, D. (2020). Integrated field surveying and land surface quantitative analysis to assess landslide proneness in the Conero promontory rocky coast (Italy). *Applied Sciences*, *10*(14), 4793. https://doi.org/10.3390/app10144793

Vjej Ju. C. (2010). The main characteristics of the Wenchuan earthquake and its impact on hazardous geological processes. *Georisk*, 1, pp. 6–10 (in Russian)

Zienkiewicz, O. C., & Taylor, R. L. (2005). The Finite Element Method for Solid and Structural Mechanics (6th ed.). Elsevier.

Михайло ЛУБКОВ*

Полтавська гравіметрична обсерваторія Інституту геофізики ім. С. І. Субботіна НАН України, вул. Г. Мясоєдова, 27/29, Полтава, 36004, Україна, ел. пошта: mikhail.lubkov@ukr.net, тел.0955395389, https://orcid.org/0009-0009-2440-9824

ЗСУВНІ ПРОЦЕСИ В НЕСИМЕТРИЧНИХ АНТИКЛІНАЛЬНИХ ГЕОСТРУКТУРАХ

Мета досліджень – встановлення теоретичних та практичних аспектів природних та техногенних гравітаційних зсувних деформацій та руйнувань на основі варіаційного скінченноелементного методу розв'язання задачі пружності для несиметричних багатошарових ортотропних оболонок обертання із урахуванням зсувної жорсткості. Для цього на основі зазначеного методу здійснено моделювання зсувного деформування та руйнування неоднорідних тривимірних несиметричних антиклінальних геоструктур в умовах дії сили тяжіння. Методика досліджень. Запропонований у цій роботі варіаційний скінченноелементний метод розв'язання задачі пружності багатошарових ортотропних оболонок обертання, з урахуванням зсувної жорсткості, дає змогу адекватно на кількісному рівні розрахувати ступінь деформування та критерії руйнування несиметричних тривимірних неоднорідних геоструктур в умовах дії сили тяжіння із метою виявлення відповідних кількісних закономірностей, що становить безумовний теоретичний і практичний інтерес. Основним результатом роботи є встановлення закономірностей зсувного деформування несиметричних антиклінальних геоструктур під дією сили тяжіння. Виявлено, що амплітуди зсувного деформування залежать від ступеня несиметричності, розмірів структури та механічних властивостей порід, що утворюють ці геоструктури. У твердих геоструктурах, що зберігають пружні властивості, зберігається також обернено пропорційне деформування відносно жорсткості навколишніх порід. Показано, що наявність нежорсткого зовнішнього шару спричиняє істотний вплив несиметричності форми антиклінальних геоструктур на їх зсувне деформування, що може призводити до критичних кількісних та якісних змін й руйнування геоструктури. Науковою новизною досліджень є встановлення деяких кількісних закономірностей, щодо зсувного деформування несиметричних антиклінальних геоструктур під дією сили тяжіння. Показано, що зменшення радіуса геоструктури призводить до зменшення деформування відповідної геоструктури, збільшення лінійних розмірів геоструктури – до зростання амплітуд деформування відповідної структури, наявність нежорсткого зовнішнього шару – до істотного впливу несиметричності форми антиклінальних геоструктур на їх зсувне деформування. Практична значущість роботи полягає у можливості на основі кількісних оцінок передбачити та забезпечити мінімізацію руйнівних зсувних процесів у несиметричних антиклінальних геоструктурах під дією сили тяжіння.

Ключові слова: комп'ютерне моделювання, розв'язання задачі пружності шаруватих оболонок, гравітаційні зсуви неоднорідних несиметричних антиклінальних геоструктур.

Received 07.07.2014