UDC 550.36. + 551.1/.4

Andrii ZYHAR[1a], Ihor SAVCHYN[2], Yuriy YUSHCHENKO[1b], Mykola PASICHNYK[1c]

[1] Yuriy Fedkovych Chernivtsi National University, 2, Kotsyubynskoho Str., Chernivtsi, 58012, Ukraine,
[1a] https://orcid.org/0000-0002-3882-8829, [1b] https://orcid.org/0000-0001-5616-8089, [1c] https://orcid.org/0000-0001-9378-6302
[2] Lviv Polytechnic National University, Institute of Geodesy, 6, Karpinski Str., Lviv, 79013, Ukraine, https://orcid.org/0000-0002-5859-1515

https://doi.org/10.23939/jgd2021.01.017

ANALYSIS OF INCLINOMETRIC OBSERVATIONS AND PREDICTION OF SOILS DEFORMATIONS IN THE AREA OF THE DNISTER PSPP

Purpose. The aim of the research is mathematical analysis and forecasting of dispersive soils behaviour based on the study of inclinometric observations data in the area of the natural-technical system of the Dnister PSPP. Methodology. The research methodology is based on mathematical analysis and modelling of processes occurring in the mountain massif on which the Dnister PSPP is located, using the finite element method. Results. The paper presents an analysis of the results of geotechnical monitoring of the behaviour of dispersive soils, implemented on the basis of inclinometric measurements on the territory of the Dnister PSPP. Quantitative parameters of horizontal displacement distribution in inclinometric wells are established. They made it possible to detect negative dynamics in the geological horizons $N_{1-2}ap$ and N_1p+v, which is apparently caused by technogenic load caused by the Dnister upper reservoir. The behaviour of dispersive soils under the influence of natural and technogenic loads has been modelled. Based on the simulation results, the change of the sign of deformations under the influence of additional load, which can be the filling of the Dnister upper reservoir, is confirmed. Obviously, the use of this method alone does not allow full detecting and tracking modern geological, seismic and geodynamic processes. A combination and detailed analysis of different monitoring methods (geophysical, geodetic, parametric, vibrometric, hydrogeological, temperature, visual-instrumental and others), as well as modelling the behaviour of the object under the influence of natural and technogenic factors is optimal. Such simulations could be used in the design of other objects of this type, so this is a promising area for further research. Originality. For the first time, a mathematical analysis and forecasting of the behaviour of dispersed soils in the area of the natural and technical system of the Dnister PSPP was conducted on the basis of studying the data of inclinometric observations. Practical significance. The proposed technique can be used in the design of other objects of this type, as modelling the behaviour of the object under the influence of natural and technogenic factors makes it possible to assess possible risks and prevent them.

Key words: geotechnical monitoring; dispersive soils; stress-strain behaviour; inclinometric wells; Dnister PSPP.

Introduction

Dnister PSPP is located 8 km northeast of the city of Sokyryany, Chernivtsi oblast (48°30′49″N, 27°28′24″E).

Fig. 1. Location map of the study area.

Its construction began in 1983. At the present time, the first stage of construction has been completed – 3 storage pumps (out of 7 designed). As a result of the construction of the Dnister PSPP, the Dnister upper reservoir was formed with a water-surface area of 1.3 km^2 (design area 3.0 km^2) and an active capacity – 11.45 km^2 (project capacity 32.70 km^2) [https://uhe.gov.ua/]. The Dnister upper reservoir is located on a plateau 125 m above the level of the Dnister buffer reservoir and was built by excavation and embankment of soil into the bottom screen and dam fencing up to 20 m in height.

It is known that the construction and operation of large-scale hydraulic structures are always associated with technology-related risks – structural, hydrodynamic, geological, geodynamic and, sometimes, seismic. Savchyn & Pronyshyn, 2020 note that the Dnister PSPP is built in complex engineering and geological conditions, characterized by a large difference in elevation and cleves between the Dnister buffer reservoir and the Dnister upper reservoir, landslide activity, the danger of water filtration in lower levels. In the process of construction of the Dnister PSPP there were serious technogenic interventions in the defined natural structure of the solid mass, as well as in the processes that take place in it. The cyclical operation of the station also leads to additional technogenic load, including changes in the hydrodynamic regime [Sidorov et al., 2015]. The process of construction and operation of such a facility must be accompanied by observation of horizontal and vertical movements of the Earth's crust, as well as a detailed analysis of deformation processes. Continuous monitoring and control of such processes can protect against disasters and their consequences, or prevent them. Therefore, all basic methods of geotechnical monitoring are applied at the construction site of the Dnister PSPP: visual-instrumental, geodetic, parametric, vibrometric, hydrogeological, temperature and geophysical methods. For example, according to [Savchyn, & Vaskovets, 2018] and [Savchyn, & Pronyshyn, 2020], since 2003, observations of slope deformations in the area of the main hydropower facilities based on GNSS measurements have been carried out on the territory of the Dnister PSPP. The authors found that modern local horizontal movements in the area of the Dnister hydropower complex have an uneven pulsating alternating character. This leads to the emergence of zones of extreme values of compression and transtension, which in most cases changed the sign to the opposite after filling the Dnister upper reservoir. GNSS methods should be used to monitor surface deformation processes, but they do not allow controlling the internal deformation processes that occur in the middle of the slope. It is generally accepted to use traditional mobile and/or fixed inclinometers to study internal deformation processes. Such methods were applied to monitor the deformation processes of the Three Gorges Reservoir (China) [Yin, et. al., 2010; Hu, et. al., 2015; Yin et. al., 2016]. The main disadvantage of traditional mobile inclinometers is the need for manual measurements at each depth, which are not effective enough due to the impossibility of real-time monitoring. Much more efficient is the use of automated fixed inclinometers, which allow real-time monitoring. The main disadvantage of fixed inclinometers is the relatively high cost and limited number of control points.

The use of monitoring based on inclinometers makes it possible to obtain real and immediate information about the vector and speed of movement of geological layers under the influence of technogenic load. But it complicates the determination of the stress in absolute numerical values, since the rocky ground, in which the measurements are carried out, is in many cases inhomogeneous and anisotropic, and the underground environment is not very conducive to measuring the smallest stress.

Geophysical monitoring at the Dnister PSPP is represented by a network of extensometric wells; as part of the modernization of equipment in 2018, two modern inclinometric wells were commissioned. This will qualitatively improve the monitoring of unique buildings and structures of the Dnister PSPP. Evidence of the given inclinometric data points creates the need for a mathematical analysis and forecast of the behaviour of dispersive soils in the area of the natural and technical system of Dnister PSPP.

Purpose

The aim of the research is mathematical analysis and forecasting of dispersive soils behaviour based on the study of inclinometric observations data in the area of the natural-technical system of the Dnister PSPP.

Data and Methods

To study the stress-strain behaviour of soils within the mountain plateau, on which the Dnister PSPP is located, two inclinometric wells no. 1 and no. 2 were identified (Fig. 2). The wells cover two main structural and stratigraphic complexes that take part in the geological structure of the region – the basement of the East European Platform (the Proterozoic) and its sedimentary cover (Phanerozoic formations) (Geological map of Ukraine, 2008).

The Proterozoic is represented by the Berdychiv ultrametamorphic complex ($\gamma \mathrm{mPR}_1\mathrm{bd}$). It is composed of andradite-biotite granitic rock and migmatite. Structurally, andradite-biotite granitic rock and migmatite are observed in synformal structures. Sediments of the Vendian system in the study area are represented by the Grushkin (V_1gr), Mogyliv (V_2mg), Yaryshiv (V_2jr), Nagoryany (V_2ng) and Danyliv (V_2dn) stratigraphy assises. These are terrigenous rock masses composed of sandstones, siltstones and argillites. The rocks described below overlap with stratigraphic inconsistencies with Cretaceous formations. Nezvyska and Pylypchany stratigraphy assises are joined ($K_{1-2}nz+pl$) – quartz-glauconitic sand is in basal layers, glauconitic sands, arenaceous limestone with glauconite are above. The age of Nezvyska stratigraphy assise is defined as Cenomanian. Ozarynets stratigraphy assise (K_2oz) is represented by limestone with admixtures of clay material and single contractions of flints. Above, there is a rottenstone with a bundle of opal and chalcedony flints. Neogene formations are represented by deposits of Baden (N_1pd) and Sarmatian (N_1p+v) regional stages and the thickness of alluvial deposits of ancient terraces of the Dnister ($N_{1-2}ap$). Sediments of the Baden regional stage are composed of sands and sandstones, and argillaceous sandstones in the upper part. Sarmatian sediments are represented by different genetic types – marine, lagoon and continental. Lithologically, they are represented by clays, sands, and limestone. The section of the investigated area is completed by ancient alluvial formations, which are represented by coarse-grained sand-gravel-pebble deposits. It should be noted that the Neogene weak and unstable layers were removed during the construction of the Dnister upper reservoir.

The stratigraphic location of the geologic horizon for both inclinometric wells is almost the same, the azimuth of the bed strike is NW=±78°, the wells are not flooded (Fig. 3).

The drill sample was studied in the vicinity of the wells and pressiometric studies of the deformability of the rocks were performed, and the modulus of deformation of the geological layers was calculated in the laboratory [Geological map of Ukraine, 2008]. Also, in Bubniak et. al., 2020 based on the lineaments analysis it is established that the Dnister PSP is in the zone with an average density of lineaments.

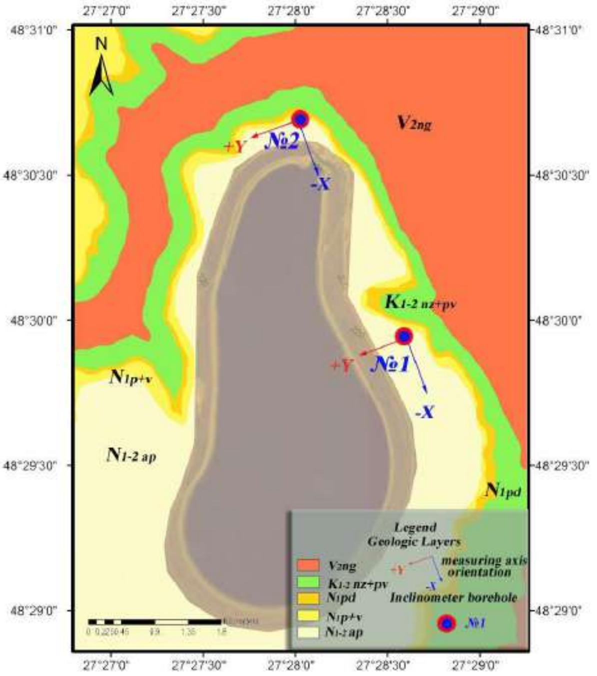

Fig. 2. Location map of inclinometric wells no. 1 and no. 2 (The map was compiled using Geological map of Ukraine, 2008).

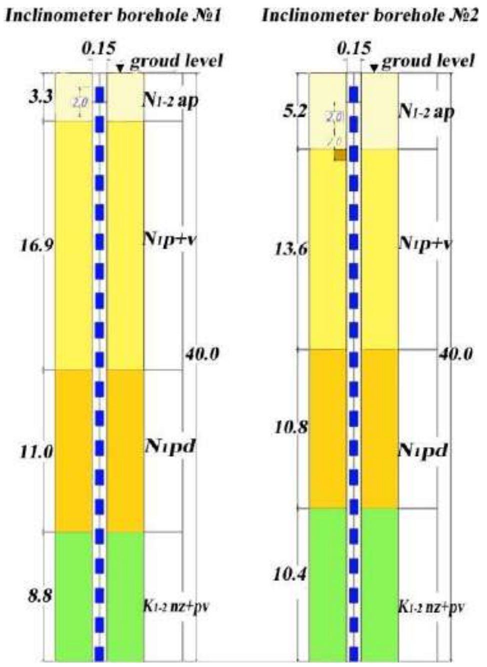

Fig. 3. Geological section along the inclinometric wells axis.

The distance between the inclinometric wells is 1400 m. The X axis is parallel to the Dnister river bed; the Y axis complements the system to the right. The inclinometric wells are equipped with 20 stationary biaxial vertical inclinometric sensors Geokon model 6150 V-2 [Geokon, 2019], with an embedding pace of 2 meters. The approximate bottom hole depth for each of the inclinometric wells is 40 meters. All sensors are automated using micro electro-mechanical system technology (MEMS). All sensors are polled automatically within the device itself 4 times a day, that is, every 8 hours. The period from 01.01.2018 to 31.12.2020 was selected for the research, during which the system received 116, 800 entries. The obtained values were averaged to one value per day for each sensor. It should be noted that the principle of operation of the sensors is based on determining the deviations of the reference mass by measuring the differential competency. With this method, both dynamic (shock and vibration) and static acceleration (tilt and rotation) can be determined.

Analysis and Interpretations

To analyze and interpret the measurement results, a transition was made from the measured inclination angles α_{xi} and α_{yi} to the displacements M_{xi} and M_{yi}, as well as to the displacement vector M_i of the i-th sensor, respectively:

$$M_{xi} = L \times \sin\alpha_{xi},\ M_{yi} = L \times \sin\alpha_{yi},$$
$$M_i = \sqrt{M_{xi}^2 + M_{yi}^2}\ , \tag{1}$$

where, L is the baseline of measurements (for the structure used in this study $L = 2000$ mm).

Having the data of the i-th (single) sensor, it is possible to determine the total displacements of the entire profile along the X and Y axes, respectively:

$$M_x = \sum_1^n M_{xi},\ M_y = \sum_1^n M_{yi}\ . \tag{2}$$

The value of displacements obtained in the course of processing along each of the axes was used to construct cumulative curves of the distribution of horizontal displacements in each inclinometric well (Fig. 4 and Fig. 5).

It should be noted that the measurement range of this type of sensors is ±10°, and with a constant position of the inclinometric well, the measurement accuracy of displacements is ±2 mm [Geokon, 2019].

Analyzing the results obtained at inclinometric well No. 1, we can note that the negative dynamics in the geological layers $N_{1\text{-}2}ap$ and $N_1p{+}v$ is subject to strong shear stress τ (in the XY plane). Layers $N_{1\text{-}2}ap$ in both inclinometric wells have a multidirectional strain vector γ, and layers $N_1p{+}v$ and below have close to unidirectional displacement along the Y axis, which indicates this type of deformation as shift fault (in the – Y direction).

It is known that as the stress grows, the deformation increases, that is, with elastic deformations, the layers $N_{1\text{-}2}ap$ and $N_1p{+}v$ would recover to their initial values when the load is released. Since this did not happen, the considered types of layers passed into the nonlinear phase of Hooke's law [Korolev, Zlochevskaya & Osipov, 1985], that is, into irreversible deformation.

The reason for these shear deformations and stresses may lie in the uneven distribution of the load on the top of the mountain plateau, in combination with dynamic fluctuations caused by the operation of the Dnister PSPP. Based on these assumptions, as well as in support of the theory of the deformation causes, it was decided to carry out computer modelling of the processes occurring in the rock mass applying finite element method [Zienkiewicz, et al., 1971; Paswey, & Clough, 1971; Pawsey, 1970; Too, 1971; Howlett, 1966; Sokolnikoff, & Specht, 1956; Scordelis, & Lo, 1964; Bakhrebah, & Schnobrich, 1973; Davoodi, et al., 2018; Mirassi, & Rahnema, 2019].

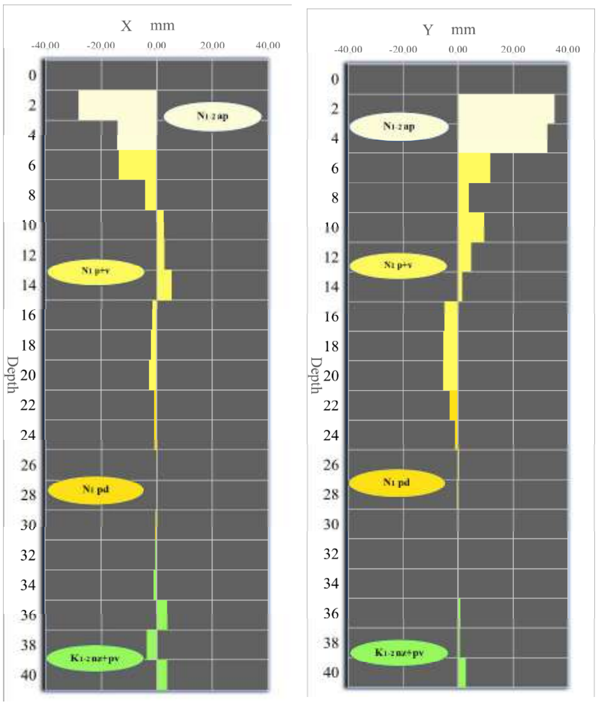

Fig. 4. Cumulative horizontal displacement profiles of inclinometric well no. 1.

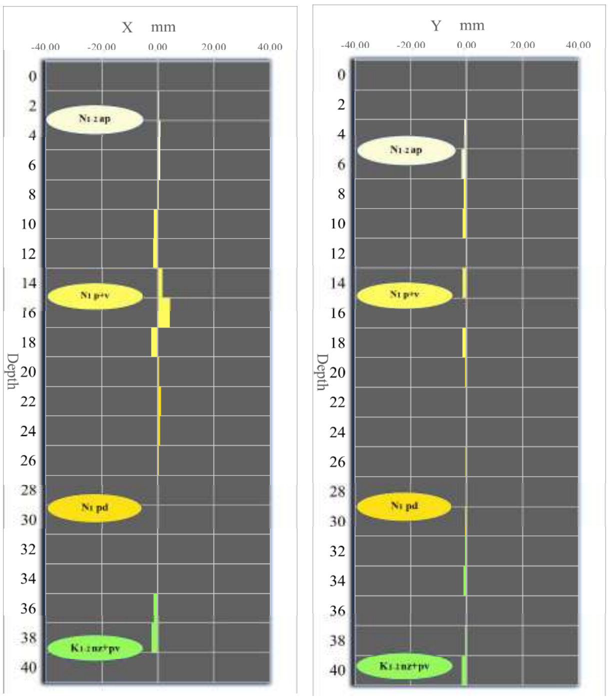

Fig. 5. Cumulative horizontal displacement profiles of inclinometric well no. 2.

Due to the limited computing power, the modelling environment was taken as isotropic; the degrees of freedom (pinching) for the model are as close as possible to the natural ones. The Winkler foundation hypothesis [Potapov, 2014] (elastic foundation) was applied to the model.

To determine the stress state at a specific point, and subsequently in solid, it is required to determine the stress tensor $T\sigma$, the components of which are three components of normal (σx, σy, σz) and six tangential ($\tau xy=\tau yx$, $\tau yz=\tau zy$, $\tau zx=\tau xz$) stresses to characterize a point in the most general case. This tensor $T\sigma$ belongs to a second-rank tensor, so it can be represented both as a series of linear equations and in the form of a matrix [Tsyitovich, 1963; Tsyitovich, 1973; Benjamin, & Cornell, 1970; Tonon, Bernardini & Mammino, 2000]:

$$T\sigma = \begin{matrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{matrix} \qquad (3)$$

It should be noted that the sequence of indexes for the components of tensor (3) characterizes the orientation of the components.

It is known that different types of stress cause different types of deformation, as follows:

- normal stress σ – causes normal deformations (e),
- tangential stresses τ – cause tangential deformations (γ),
- volumetric stresses σv – cause volumetric deformations (ev).

Positive values of stresses and strains characterize compression, negative values - transtension.

Similarly, to stress tensor (3), the strain tensor ($T\varepsilon$) can also be written as follows:

$$T\varepsilon = \begin{matrix} \varepsilon_x & \frac{1}{2}Yxy & \frac{1}{2}Yxz \\ \frac{1}{2}Yyx & \varepsilon_y & \frac{1}{2}Yyz \\ \frac{1}{2}Yzx & \frac{1}{2}Yzy & \varepsilon_z \end{matrix} \qquad (4)$$

Since the shear deformation is carried out in two mutually perpendicular directions, the tangent components of the deformation tensor (4) are divided into two.

This study will focus on geological layers $N_{1\text{-}2}ap$ and N_1p+v, which are of particular concern. The main physical and mechanical properties of these layers are presented in Table 1.

Table 1

Physical and mechanical properties of soils

Geological indicator	Density (γs), 10^4 N/m^3	Shear resistance		Poisson's ratio (μ)	Deformation modulus (E), MPa
		Internal friction coefficient (tg φ)	Adhesion ratio (C_0), MPa		
$N_{1\text{-}2}$ap	2.00	0.45	0.25	0.22	20
N_1p+v	1.97	0.75	1.50	0.25	500
N_1pd	2.05	0.30	0.35	0.30	50
$K_{1\text{-}2}$nz+pl	2.20	0.50	0.20	0.33	120

The value of the indicator ($tg\ \varphi$) (see Table 1) can be interpreted as an indicator of the number of defects in the soil. In the natural state, these defects are held together by the so-called structural bonds (Masoom et. al., 2016), at a rupture of which the soil turns into a decompressed state and tends to form an angle of depositional gradient based on Coulomb's theory [Vainberg, 1993] on the correlation between tangential and normal stresses (Fig. 6).

It follows from this that in the field of mechanical stresses from the operation of the Dnister PSPP, the coefficient of internal cohesion c_0 of the geological layer $N_{1\text{-}2}ap$ tends to zero (0.25 → 0).

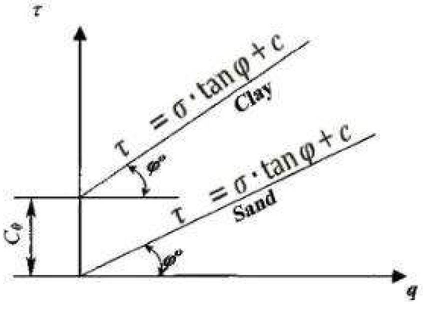

Fig. 6. Illustration for Coulomb's theory.

Also, due to the non-closedness of the geological system, there is an outflow, and possibly the extraction of moisture from the soil, which reduces the pore pressure. According to the Karl Terzaghi theory, the higher the pore pressure – u, the less external mechanical pressure σ is transferred to the soil skeleton. [Terzaghi, 1962; Herget, 1973; Terzaghi, Peck, & Mesri, 1996; Vainberg, 2012; Vainberg, 1993]:

$$\tau = (\sigma - u) \cdot \boxtimes\varphi + \mathrm{c} \qquad (5)$$

The calculation scheme (Fig. 7) was used to model the processes occurring in the rock mass based on the finite element method.

The proposed scheme (see Fig. 7) was used to perform modelling for two conditions:

- the solid mass is in natural (native) stress fields ($D\sigma_z = 0$ MPa);
- the solid mass is affected by mechanical stress fields ($D\sigma_z = 0.28$ MPa,).

Also, in modelling processes the static load deviator (D) was the mass of the dam structure, the model material was isotropic and corresponded to the parameters of the geological layer $N_{1\text{-}2}ap$ (see Table 1) and $F_g = const$.

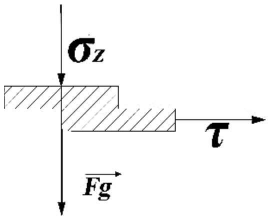

Fig. 7. Calculation scheme for modelling processes occurring in a rock mass.

The modelling allowed us to obtain the distribution scheme maps of natural (native) (Fig. 8) and mechanical (Fig. 9) stresses of the region under study.

Analyzing the obtained results, it is possible to trace the relationship between normal and tangential stresses in the solid mass under natural conditions (see Fig. 8) and in the fields of mechanical stresses emanating from the operation of the Dnister PSPP (see Fig. 9). Under natural conditions, the maximum tangential stresses for compression were 3.554 MPa, and for tensile stresses were 1.337 MPa. With a load of 0.2 MPa, the compression ratios increased to 20 MPa, the tensile strength to 2.77 MPa, most of the total area of the plateau peak moved from the compression zones to the tensile zones. The change in the sign of deformation after filling the Dnister upper reservoir was also recorded in Savchyn & Pronyshyn, 2020. Most likely, this process led to the shear deformations in the $N_{1\text{-}2}$ap layer of the inclinometric well no.1. Since the indicators of tangential stress are not critical for a given geological layer, it is most likely in the process of consolidation, that is, a change in the level of structural connections [Tsyitovich, 1963; Tsyitovich, 1973]. According to the simulation data, the layer N_1p+v makes a natural resistance according to Newton's third law $F_1 = -F_2$. The stress differences between the layers are caused either by the local accumulation of elastic deformation or by the stress transfer under the activity of the hydraulic structure.

It is also logical to assume that the construction of the Dnister PSPP did useful work in relation to the body. It changed the stress-strain state of the rock mass, thus transferred energy $[E] = J$, which has shifted from potential to kinetic, thereby provoking an increase in the seismic background in the region discussed in Savchyn & Pronyshyn, 2020.

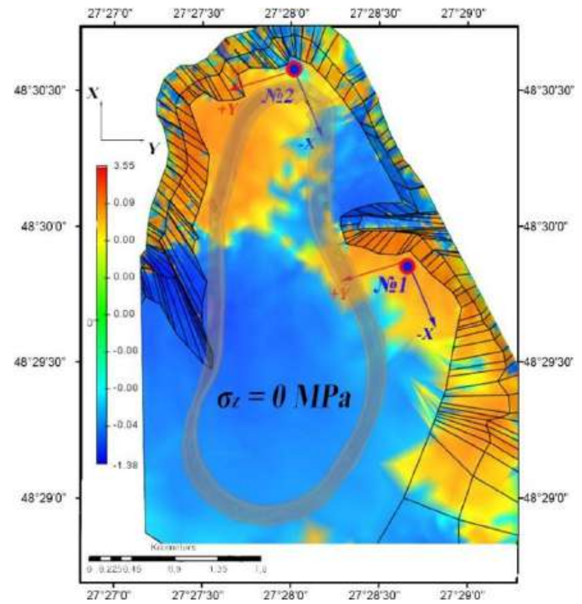

Fig. 8. Solid mass in fields at natural (native) stresses.

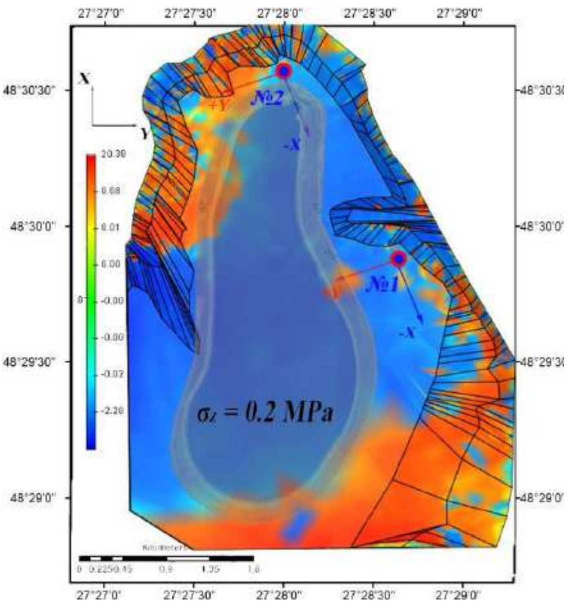

Fig. 9. Solid mass in fields of mechanical stresses.

Obtained results give us a general idea of the nature of the occurrence of some geodynamic processes arising in the field of mechanical stresses. The upper basin of the Dnister PSPP has activated and strengthened geodynamic processes in the mountain range. Continuous change of the stress-strain state can lead to a change in the structure of geological rocks, the accumulation of a fatigue effect, which will reduce the resistance of the solid mass to dynamic loads.

Originality

For the first time, a mathematical analysis and forecasting of the behaviour of dispersed soils in the area of the natural and technical system of the Dnister PSPP was conducted on the basis of studying the data of inclinometric observations.

Practical significance

The proposed technique can be used in the design of other objects of this type, as modelling the behaviour of the object under the influence of natural and tecnogenic factors makes it possible to assess possible risks and prevent them.

Conclusions and Discussion

The paper presents an analysis of the results of geotechnical monitoring of the behaviour of dispersive soils, implemented on the basis of inclinometric measurements on the territory of the Dnister PSPP.

Quantitative parameters of horizontal displacement distribution in inclinometric wells are established. They made it possible to detect negative dynamics in the geological horizons $N_{1-2}ap$ and N_1p+v, which is apparently caused by technogenic load caused by the Dnister upper reservoir.

The behaviour of dispersive soils under the influence of natural and technogenic loads has been modelled. Based on the simulation results, the change of the sign of deformations under the influence of additional load, which can be the filling of the Dnister upper reservoir, is confirmed.

Obviously, the use of this method alone does not allow full detecting and tracking modern geological, seismic and geodynamic processes. It is optimal to apply a combination and detailed analysis of different monitoring methods (geophysical, geodetic, parametric, vibrometric, hydrogeological, temperature, visual-instrumental and others), as well as modelling the behaviour of the object under the influence of natural and technogenic factors. Such simulations could be used in the design of other objects of this type, so this is a promising area for further research.

Acknowledgements

The authors express gratitude to the representatives of LLC “Hydroproject” (Kharkiv, Ukraine), PJSC “Ukrhydroproject” (Kharkiv, Ukraine) and PJSC “Ukrhydroenergo” (Vyshgorod, Ukraine) for their support and assistance in writing this publication.

References

Bakhrebah, S. A., & Schnobrich, W. C. (1973). *Finite element analysis of intersecting cylinders*. University of Illinois Engineering Experiment Station. College of Engineering. University of Illinois at Urbana-Champaign.

Benjamin, J. R., & Cornell, C. A. (1970). *Solutions Manual to Accompany Probability, Statistics, and Decision for Civil Engineers*. McGraw-Hill.

Bubniak, A. M., Bubniak, I. M., & Zyhar, A. I. (2020, May). Lineaments analysis of the Dnister area (between Bakota and Novodnistrovsk). In *Geoinformatics: Theoretical and Applied Aspects* 2020 (Vol. 2020, No. 1, p. 1–4). European Association of Geoscientists & Engineers.

Davoodi, M., Pourdeilami, A., Jahankhah, H., & Jafari, M. K. (2018). Application of perfectly matched layer to soil-foundation interaction analysis. *Journal of Rock Mechanics and Geotechnical Engineering*, 10(4), 753–768.

Geokon (2019). Instruction Manual, Model 6300, Vibrating Wire In-Place Inclinometer. https://www.geokon.com/content/manuals/6300_In-Place_Inclinometer.pdf.

Geological map of Ukraine, Scale 1: 200 000. (2008). Volyn-Podilsky series, M-35-XXVIII (Bar), M-35-XXXIV (Mohyliv-Podilsky). (in Ukrainian).

Herget, G. (1973, January). Variation of rock stresses with depth at a Canadian iron mine. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* (Vol. 10, No. 1, p. 37–51). Pergamon. https://doi.org/ 10.1016/0148-9062(73)90058-2

Howlett, J. (1966). Handbook of Mathematical Functions. Edited by Milton Abramowitz and Irene A. Stegun. Constable (Dover Publications Inc.) Paperback edition 1965. *The Mathematical Gazette*, 50(373), 358–359.

Hu, X., Zhang, M., Sun, M., Huang, K., & Song, Y. (2015). Deformation characteristics and failure mode of the Zhujiadian landslide in the Three Gorges Reservoir, China. *Bulletin of Engineering Geology and the Environment*, 74(1), 1–12.

Korolev, V. A., Zlochevskaya, R. I. & Osipov, V. I. (1985). Deformability of clay soils during compression compaction [Deformiruemost glinistyih gruntov pri kompressionnom uplotnenii] // Physicochemical mechanics of natural dispersed systems [Fiziko-himicheskaya mehanika prirodnyih dispersnyih system] / Ed. by. Schukinai E. D., MGU, 213–222. (in Russian)

Masoom, H., Courtier-Murias, D., Farooq, H., Soong, R., Kelleher, B. P., Zhang, C., ... & Simpson, A. J. (2016). Soil organic matter in its native state: unravelling the most complex biomaterial on earth. *Environmental science & technology*, 50(4), 1670–1680.

Mirassi, S., & Rahnema, H. (2019). Effect of frequency content of seismic source load on Rayleigh and P waves in soil media with cavity. *Journal of Structural and Construction Engineering*. doi: 10.22065/jsce.2019.176403.1808.

Paswey, S. E., & Clough, R. W. (1971). Improved numerical integration of thick slab finite elements. *Int. J. Numer. Meth. Eng*, 3, 545–586.

Pawsey, S. F. (1970). *The analysis of moderately thick and thin shells* (Doctoral dissertation, PhD thesis, Department of Civil Engineering, University of California, Berkeley, CA).

Potapov, V. D. (2014). About calculation of bars lying on a nonlocal elastic foundation. *Structural Mechanics of Engineering Constructions and Buildings*, 4, 63–68.

Savchyn, I., & Pronyshyn, R. (2020). Differentiation of recent local geodynamic and seismic processes of technogenic-loaded territories based on the example of Dnister Hydro Power Complex (Ukraine). *Geodesy and Geodynamics*, 11(5), 391–400. https://doi.org/10.1016/j.geog.2020.06.001

Savchyn, I., Vaskovets, S. (2018). Local geodynamics of the territory of Dnister Pumped Storage Power Plant. *Acta Geodyn. Geomater.*, 15, 1(189), 41–46. doi: 10.13168/AGG.2018.0002.

Scordelis, A. C., & Lo, K. S. (1964, May). Computer analysis of cylindrical shells. In *Journal Proceedings* (Vol. 61, No. 5, p. 539–562).

Sidorov, I. S., Perij, S. S., & Sarnavskyj, V. H. (2015). Determination of the earth surface movements in areas of Dnister PSPP using satellite and ground geodetic methods. Geodynamics. 19 (2), 15–25. doi: 10.23939/jgd2015.02.015 (in Ukrainian).

Sokolnikoff, I. S., & Specht, R. D. (1956). *Mathematical theory of elasticity* (Vol. 83). New York: McGraw-Hill.

Terzaghi, K. (1962). *Measurement of stresses in rock.* Institution of civil engineers. Geotechnique, 12, 105–124.

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). Soil mechanics in engineering practice. *John Wiley & Sons.*

Tonon, F., Bernardini, A., & Mammino, A. (2000). Reliability analysis of rock mass response by means of random set theory. *Reliability Engineering & System Safety*, 70(3), 263–282.

Too, J. J. M. (1971). *Two-dimension, plate, shell and finite prism isoparametric elements and their applications* (Doctoral dissertation, University College Swansea).

Tsyitovich, N. A. (1963). Soil Mechanics [Mehanika gruntov], 4-th Ed. Moscow, State publishing house literature on building architecture and building materials [Gos. izd-vol iteraturyi po stroitelstvu arhitekture i stroitelnyim materialam]. 638. (in Russian).

Tsyitovich, N. A. (1973). Soil Mechanics (Short Course) [Mehanika gruntov (kratkiy kurs)]. 2-nd Ed. Moscow, High school. 280. (in Russian).

Vainberg, A. I. (1993). Forces in the casing of the aggregate shafts of the Dnestrovsk water-storage electric power plant. *Journal of Mining Science*, 29(1), 27–31.

Vainberg, A. I. (2012). Numerical studies of the stress-strain state, strength and stability of the slope of the main structures of the Dnister pumped storage power plant [Chislennyye issledovaniya napryazhenno-deformirovannogo sostoyaniya, prochnosti i ustoychivosti sklona osnovnykh sooruzheniy Dnestrovskoy GAES]. Hydropower of Ukraine, (1), 48–53. (in Russian).

Yin, Y., Huang, B., Wang, W., Wei, Y., Ma, X., Ma, F., & Zhao, C. (2016). Reservoir-induced landslides and risk control in Three Gorges Project on Yangtze River, China. *Journal of Rock Mechanics and Geotechnical Engineering*, 8(5), 577–595.

Yin, Y., Wang, H., Gao, Y., & Li, X. (2010). Real-time monitoring and early warning of landslides at relocated Wushan Town, the Three Gorges Reservoir, China. *Landslides*, 7(3), 339–349.

Zienkiewicz, O. C., Taylor, R. L., & Too, J. (1971). Reduced integration technique in general analysis of plates and shells. International *Journal for Numerical Methods in Engineering*, 3(2), 275–290.

Андрій ЗИГАР[1], Ігор САВЧИН[2], Юрій ЮЩЕНКО[1], Микола ПАСІЧНИК[1]

[1] Чернівецький національний університет імені Ю. Федьковича, вул. Коцюбинського, 2, Чернівці, 58012, Україна.
[2] Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна.

АНАЛІЗ ІНКЛІНОМЕТРИЧНИХ СПОСТЕРЕЖЕНЬ ТА ПРОГНОЗУВАННЯ ДЕФОРМАЦІЙ ҐРУНТІВ В РАЙОНІ ДНІСТРОВСЬКОЇ ГАЕС

Мета. Метою досліджень є математичний аналіз та прогнозування деформацій дисперсних ґрунтів на основі вивчення даних інклінометричних спостережень в районі природно-технічної системи Дністровської ГАЕС. Методика. Методика досліджень базується на математичному аналізі та моделюванні процесів, що відбуваються у гірському масиві, на якому розташована Дністровська ГАЕС, із використанням методу кінцевих елементів. Результати. В роботі представлено аналіз результатів геотехнічного моніторингу деформацій дисперсних ґрунтів, реалізованого на базі інклінометричних вимірювань на території Дністровської ГАЕС. Встановлено кількісні параметри розподілу горизонтальних зміщень в інклінометричних свердловинах. Вони дали можливість виявити негативну динаміку у геологічних шарах $N_{1-2}ap$ і N_1p+v, яка очевидно спричинена техногенним навантаженням. Виконано моделювання деформацій дисперсних ґрунтів під впливом природних і техногенних навантажень. На основі результатів моделювання підтверджено зміну знаку деформацій під впливом додаткового навантаження, яким може служити наповнення Дністровського верхнього водосховища. Очевидно, використання виключно цього методу не дає можливості в повній мірі виявляти та відстежувати сучасні геологічні, сейсмічні та геодинамічні процеси. Оптимальним є поєднання та детальний аналіз різних методів моніторингу (геофізичних, геодезичних, параметричних, віброметричних, гідрогеологічних, температурних, візуально-інструментальних та інших), а також моделювання деформацій об’єкту під впливом природних і техногенних чинників. Такі моделювання могли б бути використані для проєктування інших об’єктів такого типу, тому це є перспективним напрямком для подальших досліджень. Наукова новизна. Вперше проведено математичний аналіз та прогнозування деформацій дисперсних грунтів в районі природно-технічної системи Дністровської ГАЕС на основі вивчення даних інклінометричних спостережень. Практична значущість. Запропонована методика може бути використана для проєктування інших об’єктів такого типу, оскільки моделювання деформацій об’єкту під впливом природних і техногенних чинників дає можливість оцінити можливі ризики та попередити їх.

Ключові слова: геотехнічний моніторинг; дисперсні ґрунти; прогнозування деформацій; інклінометричні свердловини; Дністровська ГАЕС

Received 05.04.2021