ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2022;(10-1):163–172
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 622 DOI: 10.25018/0236_1493_2022_101_0_163

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ОСЕДАНИЯ ДНЕВНОЙ ПОВЕРХНОСТИ ВСЛЕДСТВИЕ ВЛИЯНИЯ ГОРНЫХ РАБОТ ВБЛИЗИ ТЕКТОНИЧЕСКИХ НАРУШЕНИЙ

М. Журавков[1], С. Лопатин[1], М. Николайчик[1]

[1] Белорусский государственный университет, Минск, Беларусь

Аннотация: проведена оценка геомеханического и геодинамического состояний подработанного массива горных пород в зоне сочленения Северного и Центрального тектонических разломов Старобинского калийного месторождения. Данная оценка основана на численном моделировании механического поведения рассматриваемого участка массива, выполненном с использованием метода конечных элементов. Результаты численного моделирования верифицированы при помощи данных натурных наблюдений. Как численные результаты, так и данные натурных наблюдений свидетельствуют об отсутствии активизационных процессов в окрестности горных разломов на момент проведения исследований. Представленные результаты могут быть использованы для выбора технологических схем ведения горных работ в приразломных зонах, а также для прогнозирования сдвижения горных пород вблизи поверхности разлома. В результате проведенных исследований доказано, что реологические эффекты, протекающие в массиве, можно аппроксимировать путем обобщения результатов решения ряда квазистатических задач с использованием результатов натурных наблюдений в качестве проверочных граничных условий без явного учета эффектов ползучести. Точность предлагаемого метода прогнозирования оседания дневной поверхности составляет не менее 20 %.

Ключевые слова: тектонический разлом, горный массив, месторождение калийных солей, оседание дневной поверхности, метод конечных элементов.

Для цитирования: *Журавков М.*, *Лопатин С.*, *Николайчик М.* Численное моделирование оседания дневной поверхности вследствие влияния горных работ вблизи тектонических нарушений // Горный информационно-аналитический бюллетень. — 2022. — № 10-1. — С. 163–172. DOI: 10.25018/0236_1493_2022_101_0_163.

Numerical modelling of the daylight surface subsidence under the influence of mining near tectonic irregularities

M. Zhuravkov[1], S. Lapatsin[1], M. Nikolaitchik[1]

[1] Belarusian State University, Minsk, Belarus

Abstract: The article deals with the assessment of the geomechanical and geodynamic state of the undermined rock massif in the junction zone of the Northern and Central tectonic faults of the Starobinsky potash deposit. The assessment is based on numerical simulations performed using the finite element method. The results of numerical simulations are verified with the data of field observations. Both numerical results and the data of in-situ observations indicate the absence of activation processes in the vicinity of rock faults at the moment of research conduction. The results of the study can be used for selecting technological schemes for conducting mining operations in the near-fault zones and for making forecasts of shear deformation zones in the vicinity of rock faults. The study proves that it is possible to approximate the rheological effects by generalizing the results of solving a series of quasi-static problems using the results of field observations as verification boundary conditions without explicit consideration of creep effects ly. The accuracy of the proposed method for predicting daylight surface subsidence is at least 20%.

Key words: tectonic fault, rock mass, potash salt deposit, daylight surface subsidence, finite element method.

For citation: Zhuravkov M., Lapatsin S., Nikolaitchik M. Numerical modelling of the daylight surface subsidence under the influence of mining near tectonic irregularities. *MIAB. Mining Inf. Anal. Bull.* 2022;(10-1):163–172. [In Russ]. DOI: 10.25018/0236_1493_2022_101_0_163.

1. Introduction

The article presents the results of comprehensive study of the geomechanical state of the rock massif in the area of the Northern and Central rock faults taking into account mining operations. The considered area of the rock mass includes the minefields of the third and fourth mines (M3 and M4), as well as the Darasinsky mining district (MD) of the Starobinsky potash deposit. The geodynamic and geomechanical processes in this region are significantly influenced by these tectonic irregularities. The northern rock fault is situated in the north of the deposit near the Darasinsky MD and in the south of the deposit near the city of Soligorsk. The Central rock fault, in its turn, separates the western minefields M1, M2, and M3 from the eastern minefield M4. A map of the Starobinsky deposit is shown in Fig. 1 [1].

Analysis of geological and geophysical data shows that the considered section of the rock strata was in the zone of tectonic activity for the entire period of the Earth's crust formation and is located in such zone now [1]. Therefore, the complex geodynamic state in the zone of rock faults, obviously, should be under strict control when carrying out mining operations. In this regard, a system of geodynamic and geomechanical monitoring has been organized in the region to control geomechanical and geodynamic state of rock strata, as well as to achieve a balance between the issues of the mining complex and environment protection measures [2]. As part of this monitoring, geomechanical studies of the stress-strain state of the rock massif are carried out to assess the risk of dynamic disruptions and to prevent their consequences [2]. Comprehensive studies include mathematical and computer-aided modeling of geomechanical processes, which occur in the rock mass during mining operations as well as experimental studies of the rock mass deformation. The use of theoretical and computer-aided modeling approaches allows understanding the internal mechanisms of the processes taking place. Together with the results of field observations, such methods are used to develop predictive models of each particular phenomenon. In-situ observations are organized in such a way that it is possible to determine the parameters of oscillatory displacements of the rock massif and the actual displacements in the area of tectonic disturbances, caused by internal factors.

The algorithm for creating structural maps of the area in question is presented in a previous study [1]. This particular paper is a contribution to those results. In

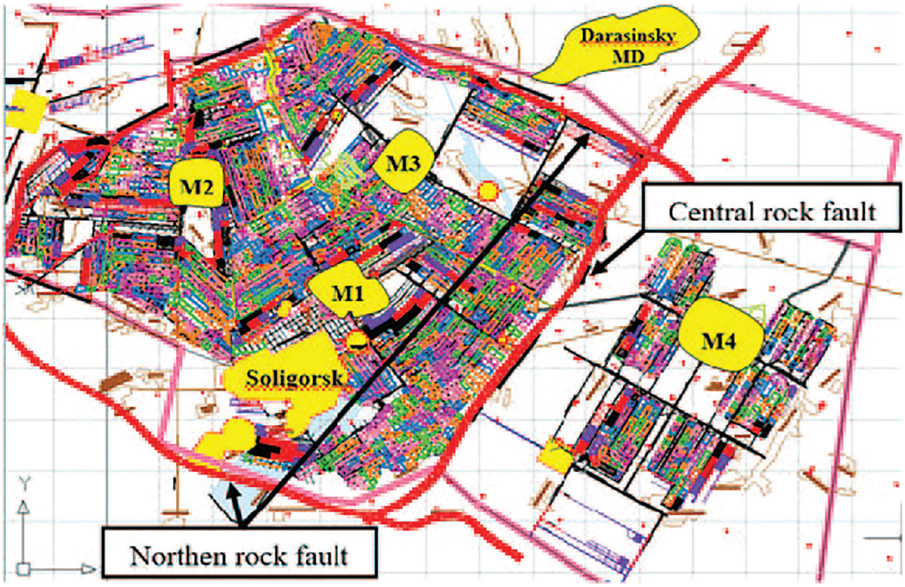

Fig. 1. Map of the Starobinsky potash deposit

previous studies it was found that computer modeling of rock massifs in the vicinity of rock faults requires a special approach due to the occurrence of significant tensile stresses in the fault zone. In addition, it was shown that the concentration of stresses in the fault zone makes the initial stress state of the rock massif with a fault different from the initial stress state of the rock massif without a fault [1]. In this paper, we conduct a sequence of model studies to predict subsidence of the daylight surface in the considered area. In each model study we use the results of in-situ observations as verification of boundary conditions, which means that each model problem can be treated as quasi-static. Rheological effects, in this case, are automatically taken into account when generalizing model studies.

The problem of determining the daylight surface subsidence is an urgent and complex task. Analysis of the vertical displacements of the daylight surface can be used to identify critical changes in the rock massif caused by mining operations or other anthropogenic causes.

To date, a number of research groups are dealing with the problem of predicting daylight surface subsidence. For example, in [3], the analysis of daylight surface subsidence at the Maogong iron mine is carried out using numerical simulation and GPS monitoring. A similar approach was used by the authors of [4]. In [5], the influence of the backfilling technological process on the rock massif displacement at nickel deposit is studied.

Numerical modelling is now widely used to solve geotechnical problems, including the problem of daylight surface subsidence. Here we cite some works that present the results of such numerical modelling. For example, work [6] is devoted to finite-element modelling of the daylight surface subsidence and soil displacements at the diamond deposit in Canada, and extensometers installed on the drifts are used to verify the numerical model. In [7], the stress-strain state of the undermined rock mass was modeled as the daylight surface subsidence was estimated using instrumental measurements. The same approach was used to estimate the daylight surface subsidence in [8]. The elastic-plastic finite-element model in [9] is used to estimate the daylight surface subsidence caused by the release of residual gas.

Daylight surface subsidence is a crucial factor for planning underground works in all sectors of the mining industry. For example, the article [10] deals with the rock mass displacements caused by mining operations in the coal-mining regions of Ukraine. Articles [11 and 12] are devoted to the prediction of the daylight surface subsidence as a result of coal mining in other regions. Forecasts of the surface subsidence in the area of gas and oil deposits are presented in [13]. In [14], in its turn, the connection between the daylight surface subsidence and internal pressure in the rock salt mines was established.

We also mention the paper [15] since the authors developed a function that shows the relationship between rock mass creep and dynamic surface subsidence. The results are confirmed by subsidence graphs. The study [16] also considers dynamic subsidence of the daylight surface under the influence of mining operations. The authors of [17 and 18] use modern methods to study the issues of daylight surface subsidence. In [17], a good correlation between differential interferometric radar data and field data of the daylight surface subsidence is shown, and in [18], an analysis of daylight surface subsidence using 3D points clouds is demonstrated.

The study [19] is devoted to the daylight surface subsidence under the influence of mining works in the regions of abandoned minefields. The nature of subsidence depending on different configurations of mining operations is examined in the article [20].

We also mention works [21,22] since they demonstrate, how important is to ensure the safety of structures which are above the ground when the underlaying rock mass is undermined as well as how the mining operations can influence the state of the undermined rock mass. Also the work [23] should be noted since it shows how the longwall mining process can affect the state of groundwater above the longwall panel which makes the research of such type crucial for safe mining.

Analysis of the literature confirms the relevance of the problem of modelling the daylight surface subsidence under the influence of mining operations. However, the analysis also demonstrates the insufficient attention to the problem of predicting the daylight surface subsidence in the area of rock faults. In this article, we demonstrate a method of predicting daylight surface subsidence in the rock fault zone, based on the analysis of field observations and numerical modelling. In-situ observations are performed along some reference lines at the geodynamic field test site in the area of the Northern and Central rock faults of the Starobinsky potash deposit [1]. This means that the geomechanical state of the undermined rock mass in the area of the rock faults junction is performed considering the actual state of mining operations.

2. Analysis of natural observations

According to the schedule of mining works, the area of mining operations near the Central and Northern tectonic faults is planned to increase by the end of 2021. Therefore, daylight surface subsidence forecasts must be made to predict the behavior of the rock massif in the area of rock faults due to the planned mining operations. The data of field observations of the daylight surface subsidence for the previous period was used as the initial data for making forecasts. The mentioned data are instrumental observations of the

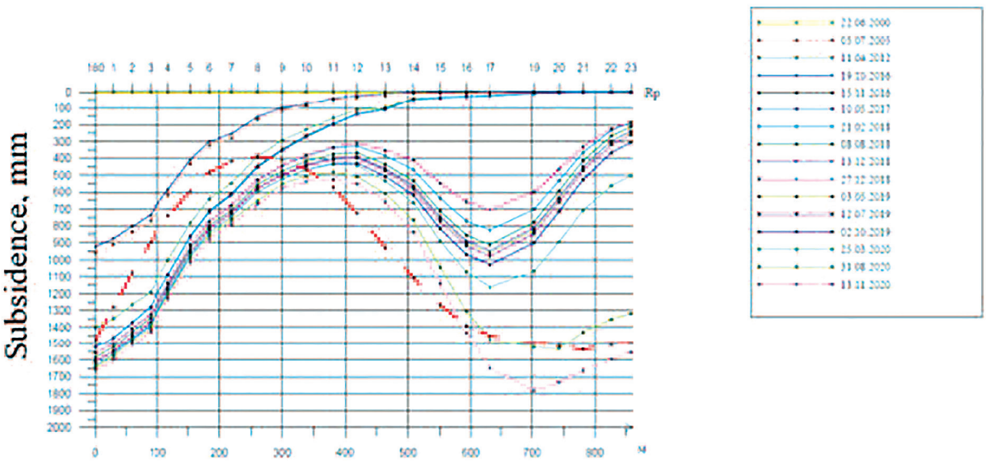

Fig. 2. Natural observations of the daylight surface subsidence along a reference line (2000—2020)

daylight surface subsidence along some reference lines for the years 2000—2021. Fig. 2 shows the daylight surface subsidence along the reference line for the entire period of observation according to the ground benchmark.

Data of field observations show that all displacements along the reference lines correspond to the classic form of daylight surface subsidence, which occurs due to mining operations. The maximum value of vertical displacement corresponds to the regions of mining operations. Over time, the values of displacements increase after mining operations. The slopes in the edge parts of the shear troughs increase with increasing subsidence of the rock mass. As a result, there is a constant increase in the values of vertical and horizontal strains overtime after mining operations. Significant fluctuations and deviations in subsidence process due to the presence of tectonic faults have not been observed in the mining area to date.

3. Numerical simulations

Finite element analysis was used to predict the daylight surface subsidence after all mining operations. A number of numerical experiments were carried out to simulate the behavior of the system “rock mass — tectonic faults — mining excavations”. The rock massif in the area of the Starobinsky potash salts deposit consists of a large number of rock layers of small and medium thickness. In this regard, the rock massif is modeled as three effective layers: sedimentary layer (0–109 m), clay-marl layer (CML, 109–558.5 m). and rock salt strata (558.5–936 m).

Mechanical properties of all rock layers were obtained using geophysical methods. Mechanical properties of the effective layers were obtained using a mathematical generalization of the properties of all layers. Table 1 shows the mechanical properties used for simulations.

The problem is solved in 3D statement, but in Fig. 3 only a cross-section of the computer-aided model is shown to demonstrate the calculation scheme more clearly. Fig. 3 focuses only on some areas of the CAD model. The full dimensions of the model are 2620x1900x936 m. The CAD model is developed based on the maps of the Starobinsky deposit [1].

Table 1
Mechanical properties of the rock mass

Effective layer name	Young's modulus, GPa	Poisson's ratio	Density, kg/ m^3	Inner friction angle, degree	Cohesion, MPa
Sedimentary layer	1	0.3	2043	11.2	0.19
CML	5	0.3	2000	38.63	1.34
Rock salt strata	14	0.3	2400	40	3

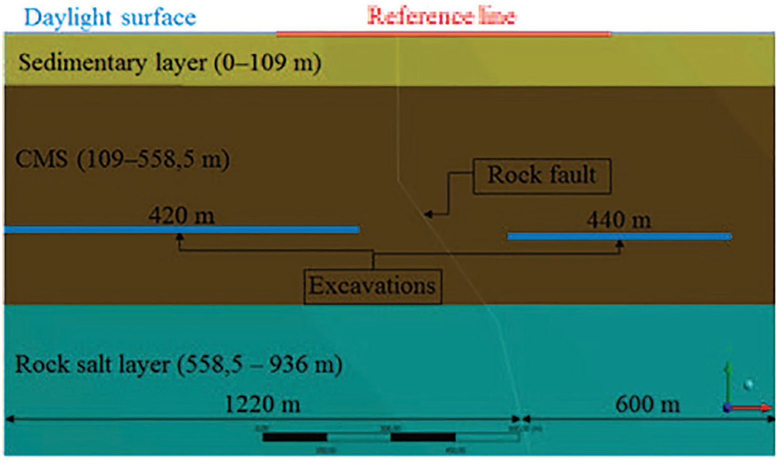

Fig. 3. Cross-section of the computer-aided model of the rock massif with rock faults and excavations

The mathematical model of the rock massif behavior includes the classical Hooke's law together with the Coulomb-Mohr model [20].

Two possible cases of the rock massif behavior in the area of rock faults were considered in the course of numerical experiments:

1) *Inactive rock fault*. In this case, it is considered that there are no activation processes in the rock fault area. This type of rock fault behavior is implemented by the bonded contact. This type of contact makes it possible to take into account the shear effects of the rock fault sides. However, shear displacements of the rock fault sides are excluded.

2) *Active rock fault*. In this case, displacements of the rock massif in the area of the rock fault are taken into account. The activity in the rock fault area is implemented using the frictional contact. The friction coefficient in this case is set equal to 0.9 along all contact areas [24, 25].

In the following, we briefly describe the numerical simulation process. To obtain numerical results, we conduct a sequence of simulations using the finite element method. After developing a CAD model of the considered area, we calculate the initial stress state using the contact elements in the area of the rock fault. Here, however, we implement the contact of a cohesive type, since previous results have shown that there were no activation processes in this area of the rock fault before the start of mining operations. At this stage, we solve the problem only in the elastic formulation, since we are not interested in the nonlinear effects that took place long before the start of mining operations. To conduct simulations at this stage, we use the following boundary conditions and other effects:

- Fixed support at the bottom of the model
- Side pressure calculated by the well-known Dinnik formula
- Self-weight of rocks
- Bonded contact between fault sides in the considered area
- Rigid contact between the effective rock layers to exclude shear displacements.

It should be noted that we need to obtain accurate results only in the vicinity of the rock fault, so the dimensions of the CAD model allow to exclude the influence of boundary conditions on the results in the considered area. The vicinity of the rock fault is defined by the reference line as shown in Fig. 2.

After the initial stress state is calculated, we simulate the behavior of the rock massif during mining operations in the considered area using these data. It should be noted that the initial strains and displacements are excluded from the calculation, so that the final results show only those values of subsidence that occurred as a result of mining operations. The boundary conditions at the second stage of calculations are similar to the previous stage. The only difference is that at this stage we conduct series of simulations using either bounded or frictional contact in the area of the rock fault as described above. At this stage, the process of simulation is divided into steps based on the order of mining operations, which is determined by the mining schedule. Mining operations are simulated via the death of finite elements that form the excavation at a particular step. This approach is well-proven, for example, in [1].

4. Results of numerical simulations

In this section, we present some results from numerical experiments. Many reference lines were studied, but we show the results for only one reference line. The figures below correspond to a reference line, which is marked in red in Fig. 3. Fig. 4 shows the daylight surface subsidence graphs as of 20.11.2020. This demonstrates the difference between the real daylight surface subsidence graph and the subsidence graph obtained by numerical simulation in the case of inactive rock fault.

Fig. 4 shows a fairly high degree of qualitative and quantitative correlation between the numerical results and field data in the case of an inactive rock fault. However, we can notice certain deviations, especially at the local extremes of the graphs. These deviations are explained by the extremely nonlinear behavior of the rock mass and the fact that the simulation does not take into account the creep of the rock mass. .In addition, the scatter of the mechanical properties of the initial rock layers is about 20%. The average relative error of the numerical calculation in the case of an inactive rock fault is 20.2%, which allows to conclude that numerical simulation performed demonstrates a good degree of accuracy.

Fig. 5 shows the same daylight surface subsidence graphs but in the case of an active rock fault. This figure demonstrates that the frictional displacements in the area of the rock fault cause a sharp spike in the subsidence graph. However, the field data show no such behavior in the rock fault area, which allows us to conclude that there are no activation processes in the case considered.

5. Conclusion

Analysis of field observations data shows that there is no significant subsidence of the daylight surface in

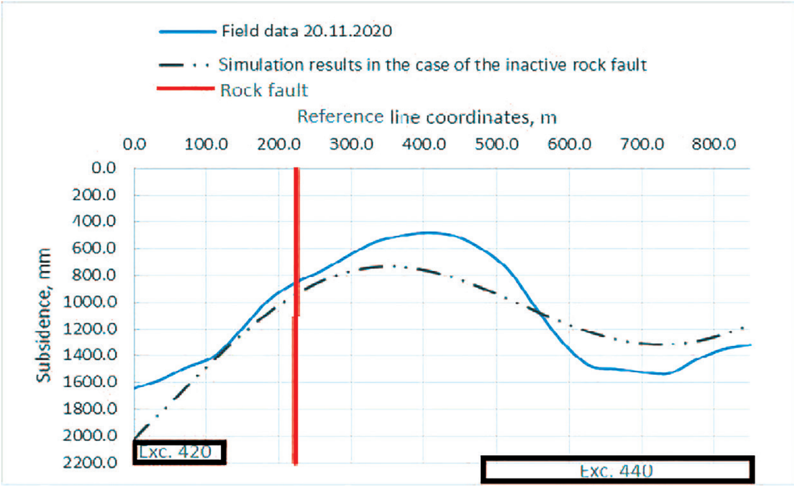

Fig. 4. Comparison of the field data and simulation results in the case of the inactive rock fault as of 20.11.2020

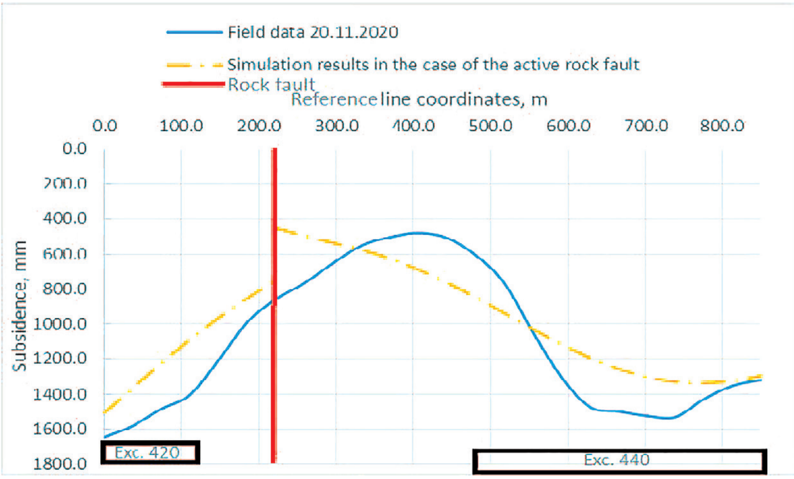

Fig. 5. Comparison of the field data and simulation results in the case of the active rock fault as of 20.11.2020

the area of the junction of the Northern and Central tectonic faults caused by mining operations. At the same time, the processes of activation of the daylight surface subsidence are in good correlation with the periods of mining operations according to the mining works schedule.

The results of the finite-element simulation, are based on the developed geomechanical model of rock mass behavior in the considered area, show a high degree of qualitative agreement of the daylight surface subsidence with the data of field observations in the case of inactive rock fault. Therefore, we can conclude that in the junction of the Northern and Central tectonic faults of the Starobinsky potash deposit, since the beginning of mining operations and natural observations, the processes of activation are still absent.

In addition, this study considers the case of the active behavior of the rock fault.

The results of numerical simulations in the case of the active rock fault have confirmed the absence of activation processes in the rock massif near rock faults caused by mining operations up to now.

However, the relative error of conducted numerical simulation is approximately 20%, which is associated with the spread of mechanical properties and the fact that the creep behavior of the rock mass was not considered directly, as mentioned in the introduction. Nevertheless, the numerical simulation results confirm the initial hypothesis that it is possible to approximate the rheological effects in the considered case by generalizing the results of a series of quasi-static problems using the results of field observations as verification boundary conditions. At the same time, it is planned to modify the model by explicitly considering creep effects when considering the following sequence of in-situ observations to improve the accuracy of the predictive model more precise.

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ИНФОРМАЦИЯ ОБ АВТОРАХ

Журавков Михаил Анатольевич[1] — доктор физ.-мат. наук, профессор, зав. кафедрой, e-mail: zhuravkov@bsu.by, ORCID ID: 0000-0002-7420-5821;
Лопатин Сергей Николаевич[1] — аспирант, e-mail: lopatinsn@tut.by, ORCID ID: 0000-0001-5958-7799;
Николайчик Михашл Александрович[1] — аспирант, e-mail: nikolaitchik.m@gmail.com, ORCID ID: 0000-0003-3733-1615,
[1] Белорусский государственный университет.
Для контактов: *Лопатин С. Н.*, e-mail: lopatinsn@tut.by.

INFORMATION ABOUT THE AUTHORS

Zhuravkov M. A.[1] , Dr. Sci. (Phys. and Math.), Head of the department, e-mail: zhuravkov@bsu.by, ORCID ID: 0000-0002-7420-5821;
Lapatsin S. N.[1] , PhD student, e-mail: lopatinsn@tut.by, ORCID ID: 0000-0001-5958-7799,
Nikolaitchik M. A.[1], PhD student, e-mail: nikolaitchik.m@gmail.com, ORCID ID: 0000-0003-3733-1615.
[1] Belarusian State University, 220012, Minsk, Republic of Belarus.
Corresponding author: *Lapatsin S. N.*, e-mail: lopatinsn@tut.by.

Получена редакцией 20.03.2022; получена после рецензии 27.06.2022; принята к печати 10.09.2022.
Received by the editors 20.03.2022; received after the review 27.06.2022; accepted for printing 10.09.2022.