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Numerical Modeling the Rock Mass Stress-Strain State Near Vertical Excavations in Combined Mining

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Abstract

In recent years, the development of the mining industry in the Republic of Kazakhstan has been accompanied by the commissioning of new underground levels for many existing mineral deposits, which were initially developed through open-pit mining. As the depth of open-pit mining increases, the volume of overburden rises sharply, making open-pit mining unprofitable due to the significant amount of additional mining work required. For this reason, most open-pit mines in Kazakhstan are transitioning to underground mining, or combined mining. Many researchers have examined the timing of this transition and have worked on optimizing it to determine the best economic efficiency and manage risks. However, there is limited information available on how to determine the optimal location for a vertical mine shaft when transitioning from open-pit to underground mining. The purpose of this study is to identify a safe location for a vertical shaft in combined mining operations. Specifically, the study assesses the impact of the open-pit mine on the selection of the mine shaft's location, considering the stress-strain state of the rock mass during combined mining methods. To address these objectives, numerical modeling of the stress-strain state around vertical excavations during combined mining was performed. The results provide a solution to the critical issue of determining the location of the mine shaft in combined geotechnology and lay the groundwork for further research on shaft placement in Kazakhstan. The novelty of this study lies in identifying the shaft location by considering the geometric shape of the open-pit mine and the depth of development.

Keywords: Combined Development; Stress-Strain State of the Massif; Vertical Shaft; Open Pit; Rocks; Finite Element Method.

1. Introduction

The experience of ore deposits open-pit mining (combined mining) in Kazakhstan and the world using schemes for opening sub-quarry reserves with vertical shafts is considered. Practice confirms that when minerals are located deposited in deposits, combined mining is used—first, the upper part is developed in an open way, then, based on economic feasibility, the transition to an underground method is carried out [1, 2].

A Shaft location should be determined taking into account the potential slope slickenside in combined technology [3]. It is known from theory and practice that the location of mine shafts significantly affects the capital costs of opening and preparing a deposit, transport, ventilation, drainage, etc. [4]. In order to study the problem of choosing a rational location of vertical mine shafts in conditions of combined geotechnology, previous works were studied. The well-known methods for determining the location of the shaft during the underground mining of deposits by privies studies were considered [5-7].

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Hudej et al. [6] considered in their works the issue of selecting the location of the main shaft of the Velenie mine using the multi-model analysis, the essence of which is not in selecting the most suitable method to justify decision-making but in applying the multi-model analysis, i.e., in the simultaneous use of several multi-criteria methods. The selection was made in favor of software that is widely used: the PROMETHEE, the ELECTRE, the AHP, and the VIKOR [7, 8]. The authors of this study recommend that, in the process of analysis, when it is necessary to determine priorities or rank alternatives, decisions should be associated not with the choice of method but with the procedural process of analyzing and applying the solution, which is confirmed in their case by the choice of the location of the main shaft.

Another study by Bi et al. [9] provided a numerical analysis of the model of the impact of mining operations on the stability of a shaft, which was analyzed using a three-dimensional finite program FLAG 3 D 2.1. This model was used for the Baodian Coal mine (China).

According to the researchers' analysis, during underground mining at a depth of 250 m, the bedrock under the aquifer begins to weaken, and then some cracks develop in it. Despite the fact that the crack occurs on the aquifer, the distance between the aquifer and the mine panel is far enough. The effect on the aquifer disappears during mining at a depth of 400 m, and shear deformation near the rock panel tends to increase. The depth of the shaft also affects the stability of the shaft; therefore, the maximum main stress on the surface of the shaft was used to assess the effect (near the shaft, it was about 18 MPa). The authors' research shows that the influence of the width of the security pillar is obvious for the stability of the shaft. When the width of the security pillar exceeds 70 m, the influence of the depth of development becomes greater [7].

Currently, there are works on the choice of the location of vertical shafts in the underground mining of ore and coal deposits. However, there is no most appropriate methodology and justification for this problem for the specific features of combined field development. It is known that with the underground method, the choice of opening methods, the determination of the location of the main opening excavations are carried out taking into account various natural and technical factors [10]. However, for combined development, it is possible to add additional new man-made impact factors: open pit space, areas of weakened rocks adjacent to open-pit mining, early erected surface open-pit mining facilities, etc. In these circumstances, the choice of the location of vertical shafts should be made taking into account the possibility of the most complete development of both quarry and sub-quarry reserves. In conditions of combined geotechnology, it is very important to ensure the location of vertical shafts outside the area of occurrence of minerals at some distance from the risky barrier zone of weakened rocks, with the condition of vertical shafts in safe and working condition throughout the entire period of their operation.

In the conditions of the “Ushkatyn-3” mine of JSC Zhayremsky GOK in 2009-2010, taking into account the possibility of the most complete extraction from the depths of the main and adjacent mineral reserves, scientific experimental work and calculations of the stability of open-pit mining slopes were carried out to justify the possibility of switching to combined mining in order to select a rational location (standing) of vertical shafts [11].

For this purpose, stability calculations were performed during the observations for the geomechanical model of the inhomogeneous slope of the northern and western sides of the quarry. For the calculation, the BABO method of Professor Sabdenbekuly Omirzak was used [4], which allows to determine the place where the shaft should be located outside the orebodies in order to reduce ore losses that remain in the safety pillars, when the shaft would be located in the center of the orebody [12]. In this case, the rational distance from the lower edge of the orebody to the near wall of the shaft is determined. The location of the trunk is determined taking into account the mining and geological conditions of the deposit. In this case, five geological sections are used, on which the curves of the sliding lines of rocks are applied. According to the data obtained, an analysis was carried out, and, taking into account the depth of the open-pit mine, the mechanical properties of the rocks at the site of the passage of the sections, a zone of possible displacement was determined. According to the State Industrial Safety Rules, the construction of any structures in the subsidence is prohibited [11, 13].

In case of transition from open pit mining to underground mining, there is a need to carry out in-depth scientific research in the field of geomechanics and to forecast the stress-strain state of the rock massif around mine excavations, in this case vertical shafts. In this regard, in addition to previously experimental studies, research was carried out to determine the safe location of vertical shafts using the finite element method. There are different ways to model a rock massive. Due to the possibility of rapid modeling and remodeling, one of the most promising is mathematical modeling using a PC [14]. The aim of the study was to assess the stress-strain state of the rock massif during combined mining and to select the location of the shaft.

2. Research Methodology

When assessing the stress-strain state of the rock massif using numerical methods, the finite element method has become widely used. The finite element method involves constructing a geomechanical model and its subsequent numerical study, which makes it possible to “play over” the behavior of the object under study under various conditions [15]. This method makes it possible to consider many physical and mechanical properties of rocks, the geology and structure of the massif, and the shape and dimensions of the model under study.

The complex geological structure of many deposits contains alternating weak and very weak, medium-strength, and strong rocks. The presence of fault-shear type rocks, strong fracturing of rocks, etc. entails an unstable state of both the pit side and the ledges that make up the side. But the complications of calculation schemes due to the significant uncertainty of rock contacts and their physical and mechanical properties does not bring a noticeable increase in accuracy. For this reason, when drawing up the calculation scheme for the stress-strain state of the massif, only the main enlarged elements of the geological section were considered [16, 17].

The initial data for calculating the stress-strain state of the massif are mainly geological and structural-tectonic features, physical and mechanical properties of rocks, as well as edge parameters [18]. There are various software packages for modeling geomechanical processes that assess displacements and deformations of rocks that implement the finite element method. The solution of the finite element model (FEM) of the boundary value problem is carried out in three stages. At the first stage, the basis of a finite element model of the object under study is created. This stage includes the following procedures (Figure 1) [19, 20]:

1. The physical type of the problem is set (mechanics of a deformable solid, heat transfer, hydrodynamics, etc.), and the appropriate program settings are made.
2. The type of the final element is selected depending on the dimension of the object and its other properties. Some element characteristics can be set.
3. The material of the selected object, and all its necessary properties are specified. Setting the properties determines the model of the material (linear-elastic), elastic-plastic, bilinear, etc., which affects the choice of the defining equations of the finite element method.
4. A geometric model of the object is created.
5. In the case of a contact problem, contact pairs are established, the contact model and its characteristics are determined.

The second stage—setting the necessary physical conditions on the model and computation—consists of three main steps [17, 20]:

1. Boundary conditions are set – forces, displacements, etc.
2. The type of analysis is selected (static, dynamic, modal, etc.). It is possible to choose a method for solving the FEM system of equations and setting the parameters of computational procedures (the number of loading steps, the number of iterations, etc.).
3. The system of equations obtained by the FEM method is solved. As a result of the solution, a results file is generated, which contains a vector of the degrees of freedom found (nodal displacements, nodal temperatures, etc.).

The third stage is the analysis of the calculation results [17, 20].

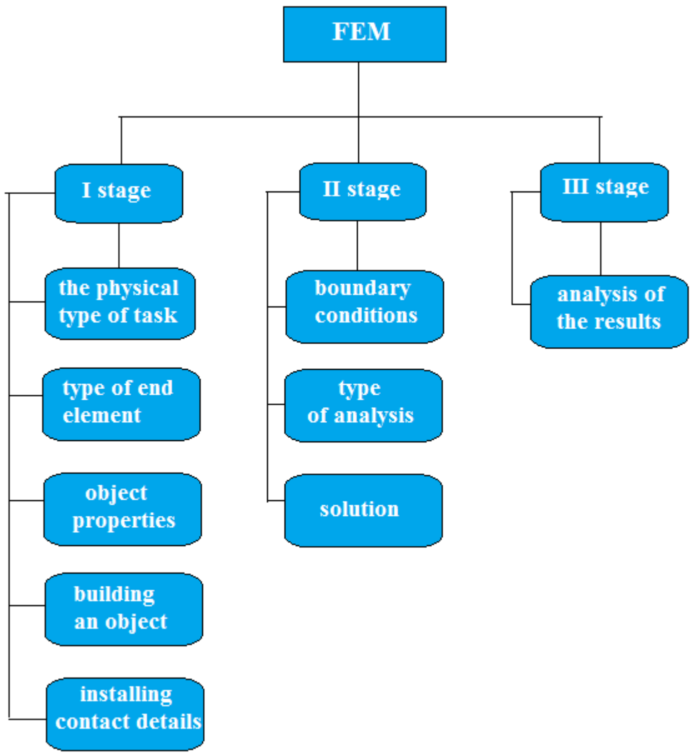


Figure 1. FEM stages

At the first stage, the geometric model is prepared, the material and its properties are specified, the finite element mesh is generated, and the physical conditions of the modeling are determined. The following parameters were used for the calculation [21]: compressive strength 80 MPa; tensile strength 8 MPa; Poisson's ratio 0.26; Young modulus 8.10×10^{-4} MPa; shear modulus 3.20×10^{-4} MPa; volumetric mass – 27 kN/m^3. The calculation is performed for a homogeneous massif. The increasing complexity of the schemes calculations due to the complex geological structure of the field and their physical and mechanical properties did not bring accuracy to the calculations. In this regard, a homogeneous massif was selected. Next, a geometric body of the object is constructed with the following parameters: The shape of the pit is ellipsoidal; the final pit depth is 100, 200, or 300 m; the shaft diameter is 10 m; and the distance between the upper edge of the open pit and the shaft varies from 100 to 300 m. The indicators of the physical and mechanical properties of the deposit rocks are adopted for the conditions of the Akzhal deposit.

The resulting geometric model was divided into finite elements (Figure 2). The entire model is divided into many finite elements that are connected to each other at the vertices. This is the basic concept of the FEM. To carry out the experiment, an ordered mesh was constructed because a refinement of the finite element mesh was required.

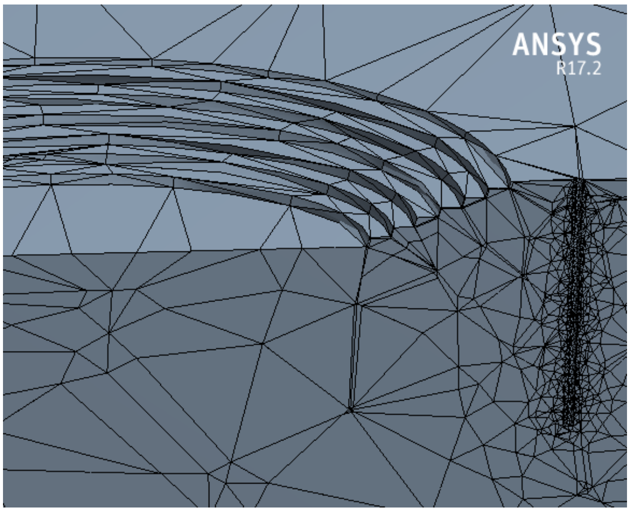


Figure 2. Dividing the object into finite elements

In the second stage, the necessary physical conditions are imposed on the model. The type of load is selected—inertial and ordinary gravity is 9.8 m/s^2. There are sets of properties of rocks, such as density, kg/m^3; Young modulus, MPa; shear modulus, MPa; and Poisson ratio. At the third stage, an analysis of the calculation results is displayed. There are three varies of the models calculating results shown in Table 1 [18, 19].

For the modeling process, the ellipsoidal open pit is visually divided into four sections. One section is selected based on various factors, and calculations are performed for this part. The chosen section must account for a new factor of anthropogenic impact: the open pit space and the adjacent zones affected by geomechanical forces. The remaining sections of the open pit are represented as being similar to the selected one. The selected section is then divided into radial directions with the following angles: 90 degrees, 67.5 degrees, 45 degrees, 22.5 degrees, and 0 degrees (Figure 3) [21].

Table 1. Model options

Option No.	Open pit depth, m	Shaft depth, m	Shaft location relative to the open pit surface	Distance from the upper edge of the open pit to the shaft, м
1	100	500	1. When the shaft is located on the line with the angle of 0 degree	100
			2. When the shaft is located on the line with the angle of 90 degrees	150
			3. When the shaft is located on the line with the angle of 45 degrees	200
			4. When the shaft is located on the line with the angle of 22.5 degrees	250
			5. When the shaft is located on the line with the angle of 67.5 degrees	300
2	200	600	1. When the shaft is located on the line with the angle of 0 degree	100
			2. When the shaft is located on the line with the angle of 90 degrees	150
			3. When the shaft is located on the line with the angle of 45 degrees	200
			4. When the shaft is located on the line with the angle of 22.5 degrees	250
			5. When the shaft is located on the line with the angle of 67.5 degrees	300

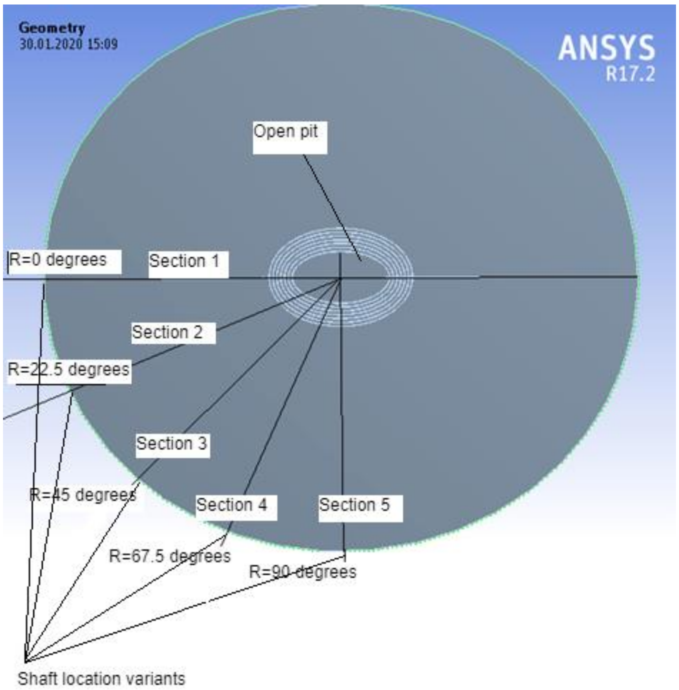


Figure 3. Radial directions

3. Results and Discussion

3.1. Results of the SSS Simulation

The stress-strain state of the massif near the shaft is presented in Figures 4-13 at the open pit depth of 100 and 200 m with distances from the upper edge of the open pit to the shaft (100, 15, 200, 250, 300 m) and at different radial directions of the open pit field 00, 22, 50, 450, 67.50, 900. As an example, the results of modeling the stress-strain state of a massif near a vertical shaft at the open pit depth of 200 m are shown.

Figure 2 shows how the zones and values of active stresses change (marked in different colors) depending on the depth of the open-pit and radial directions. Modelling shows that the sizes of high stress concentration zones depend on the open-pit depth. For practical purposes, another parameter is important; this is the distance from the upper edge of the open-pit mine to the location of the mouth of the vertical shaft, which should be safe. This value determines the safe location of the shaft mouth on the earth's surface, taking into account the stress-strain state of the rock mass not only on the surface but also throughout the depth of the vertical shaft.

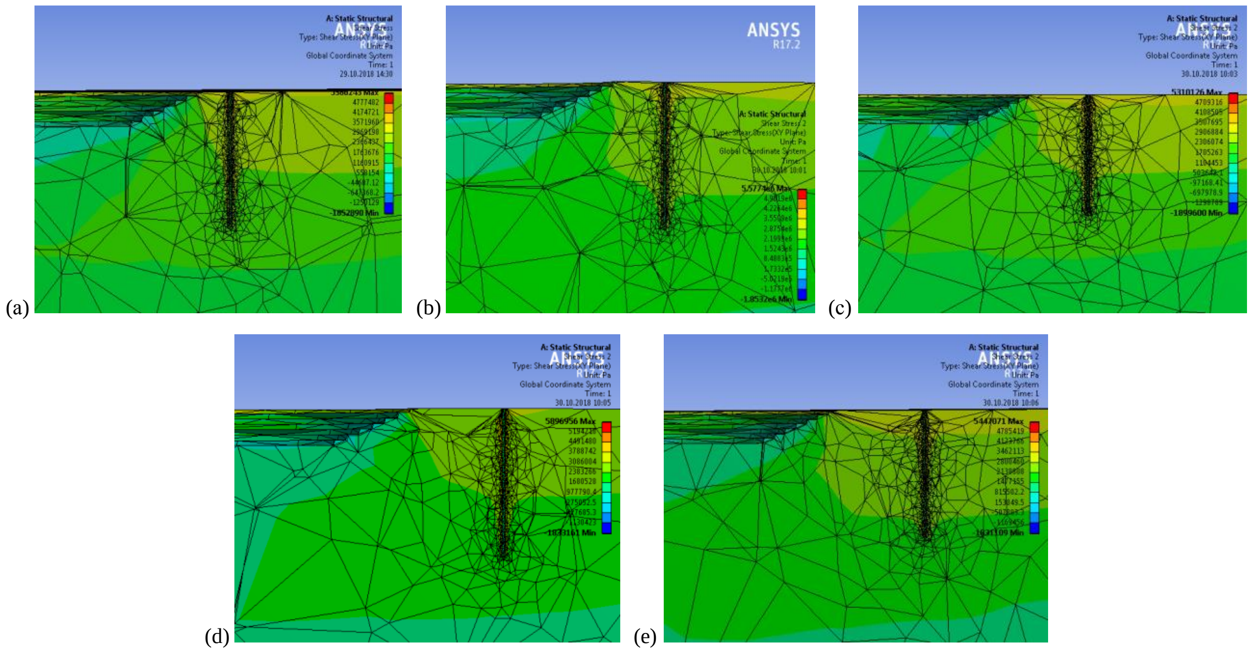


Figure 4. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 100 m, section 1); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

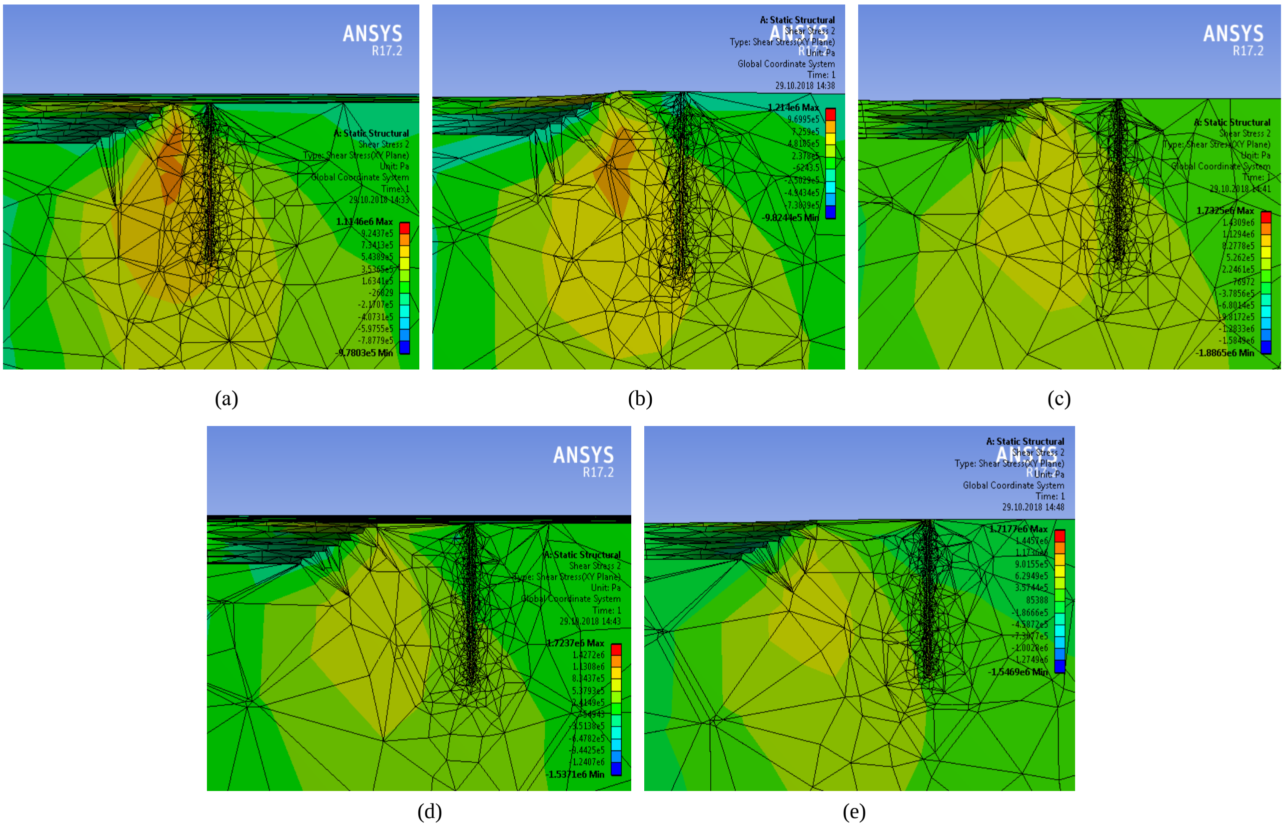


Figure 5. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 100 m, section 5); the distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

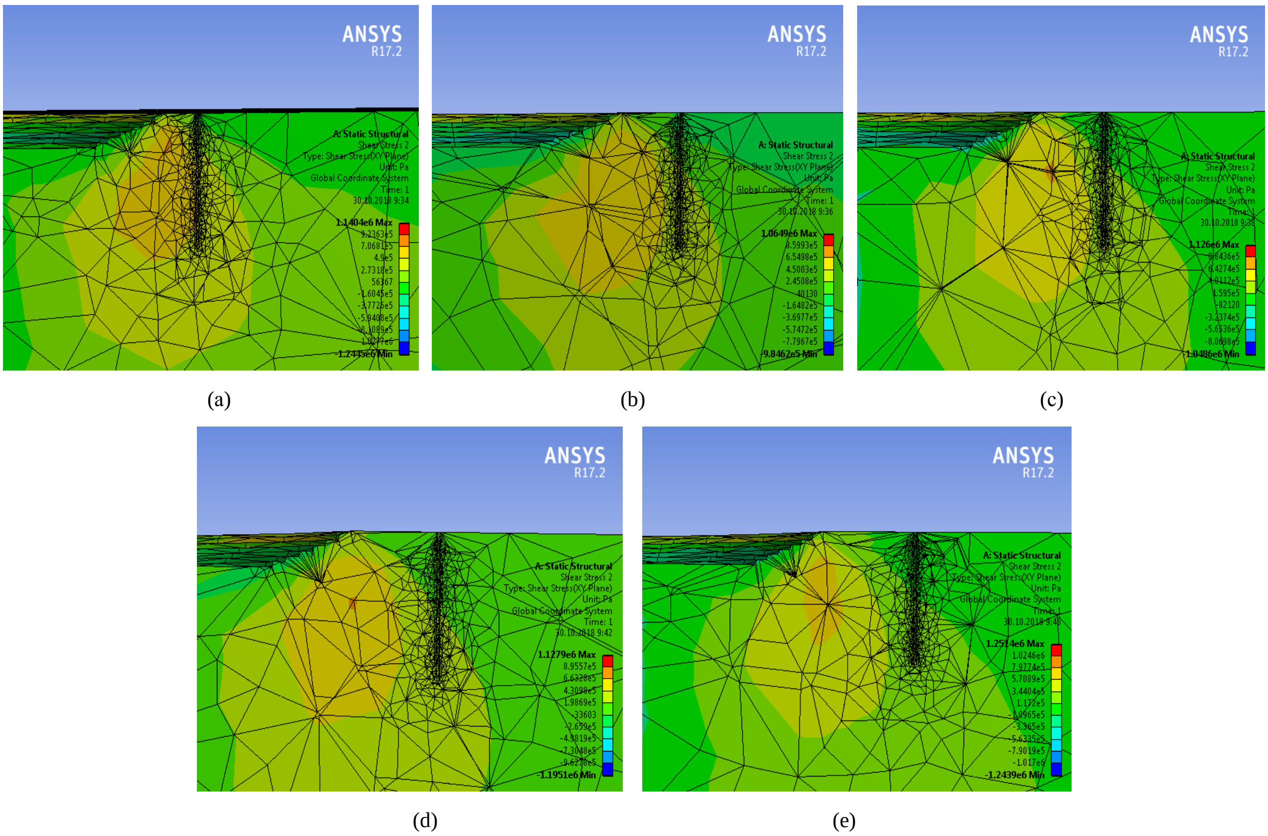
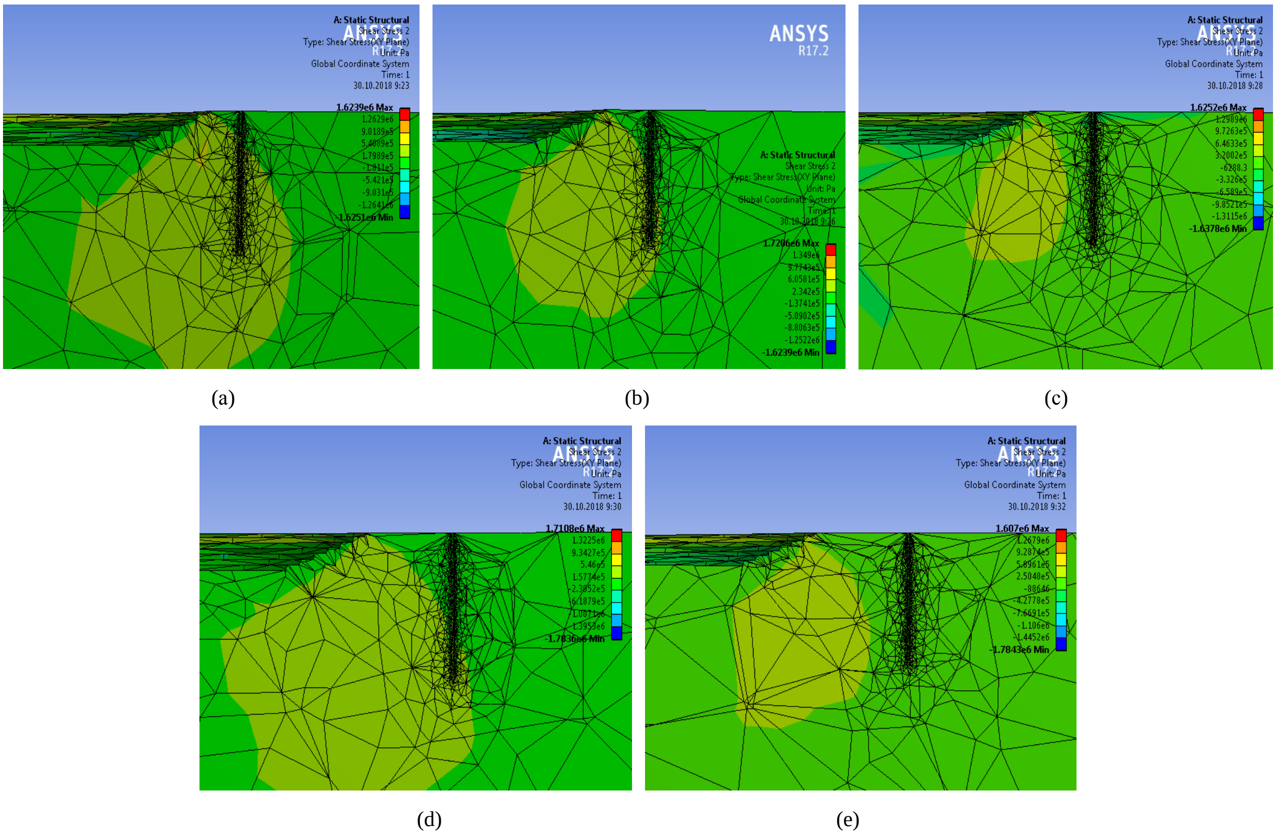
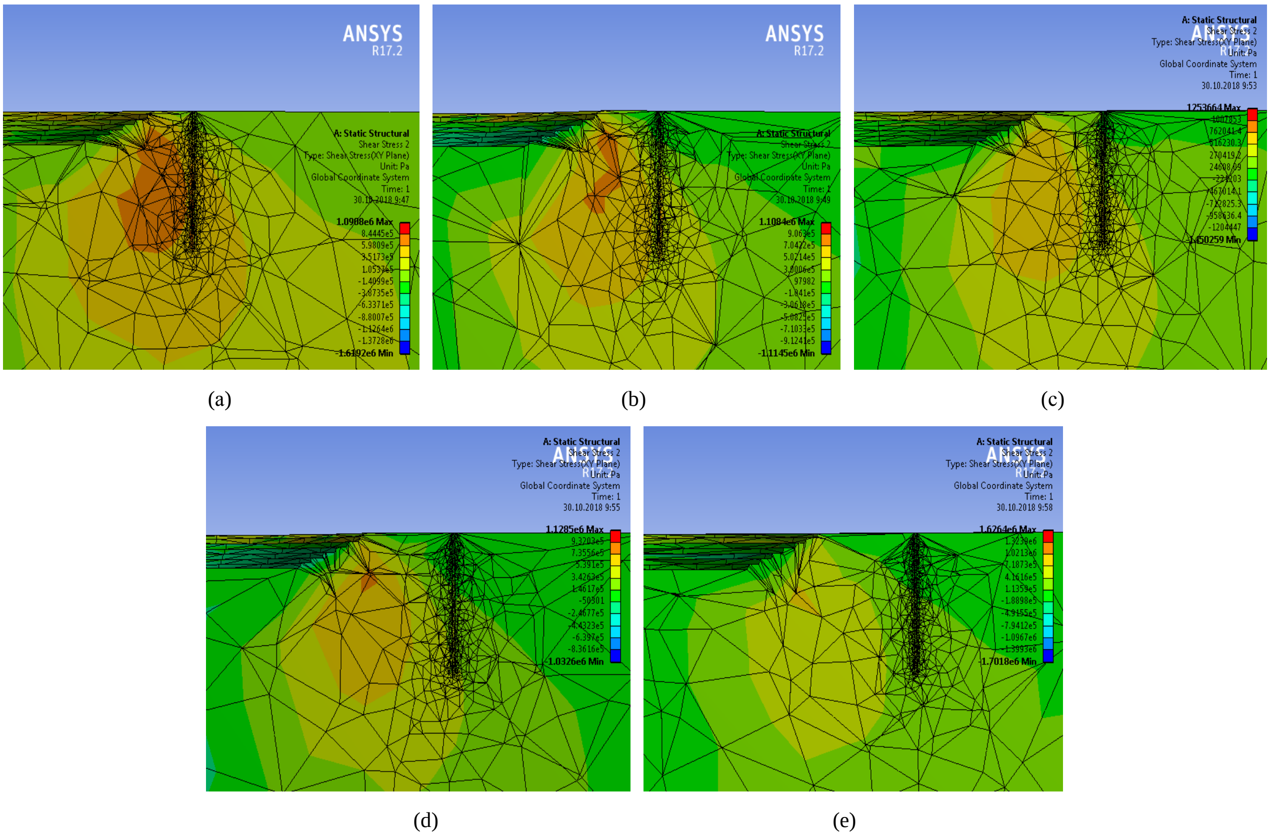


Figure 6. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 100 m, section 3); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.



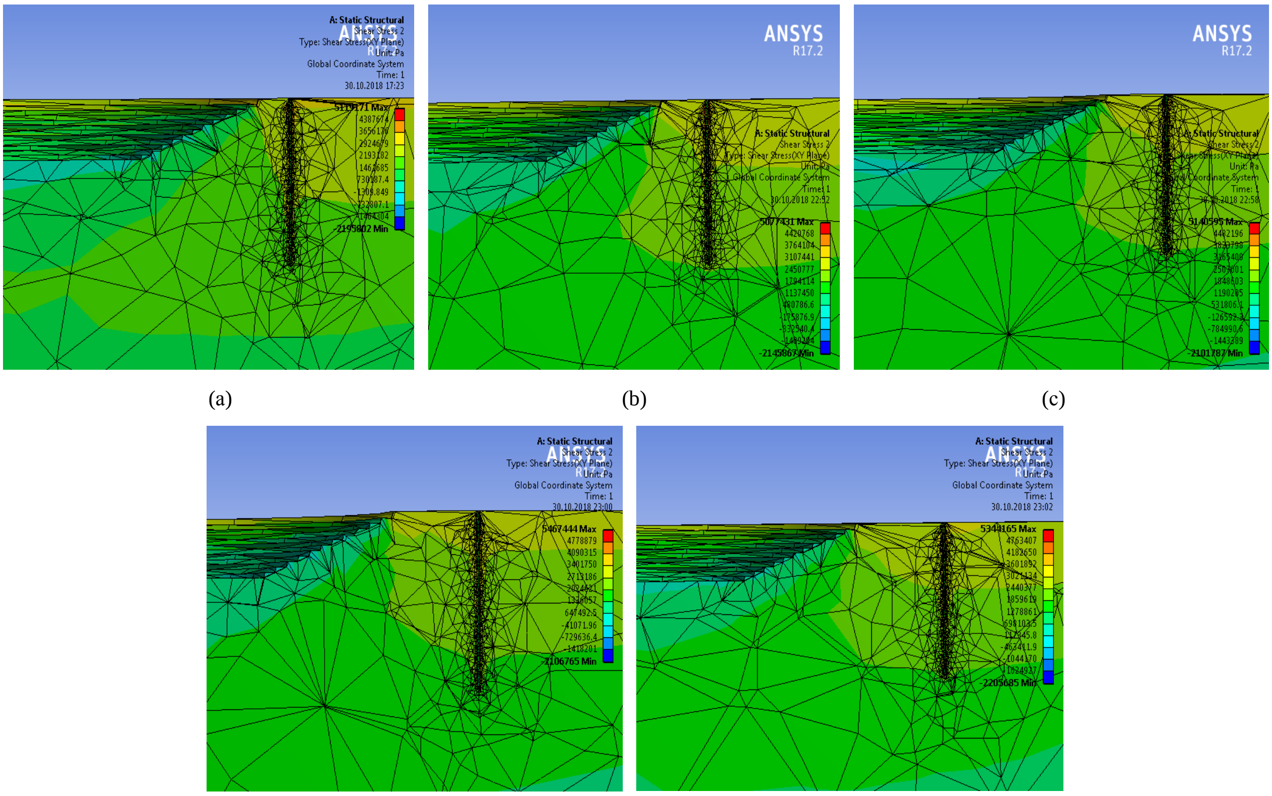
(a) (b) (c) (d) (e)

Figure 7. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 100 m, section 2); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.



(a) (b) (c) (d) (e)

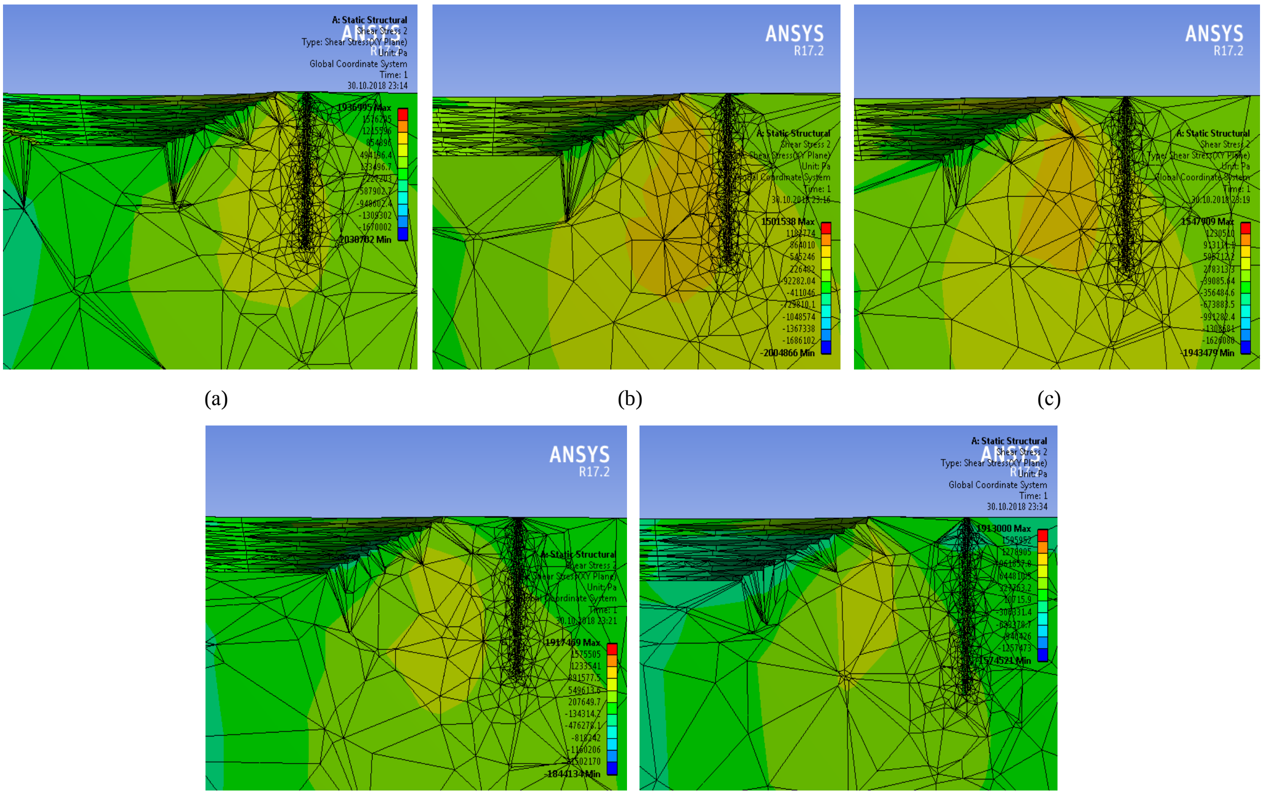
Figure 8. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 100 m, section 4); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.



(a) (b) (c)

(d) (e)

Figure 9. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 200 m, section 1); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.



(a) (b) (c)

(d) (e)

Figure 10. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 200 m, section 5); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

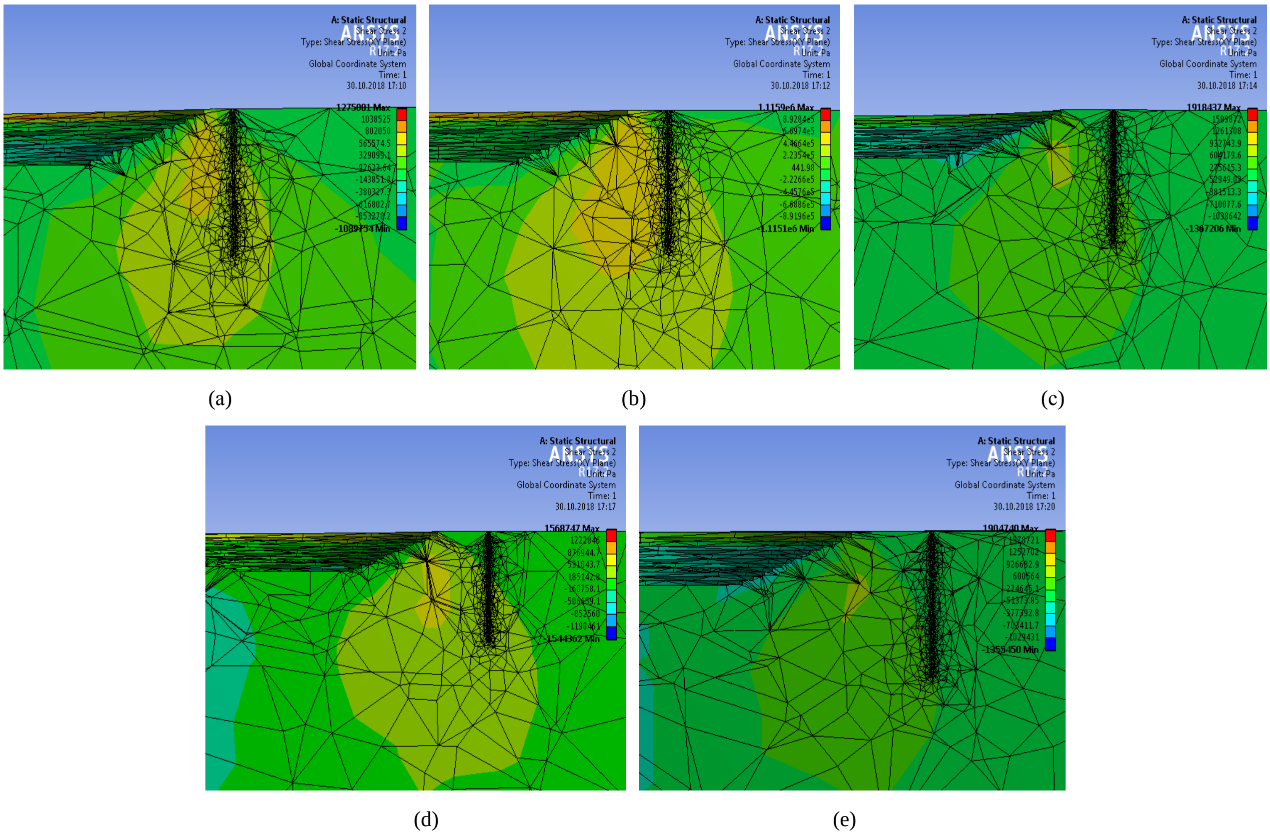


Figure 11. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 200 m, section 3); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

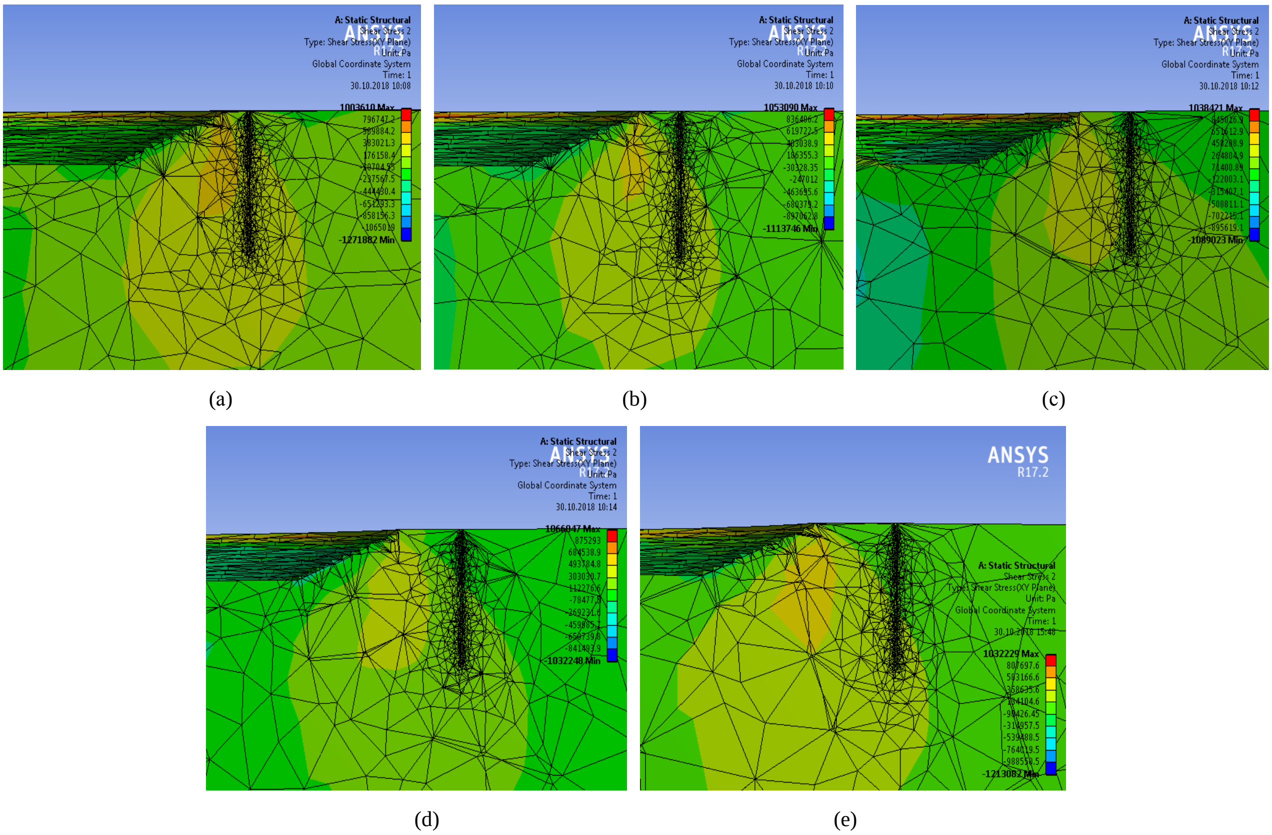


Figure 12. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 200 m, section 2); the distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

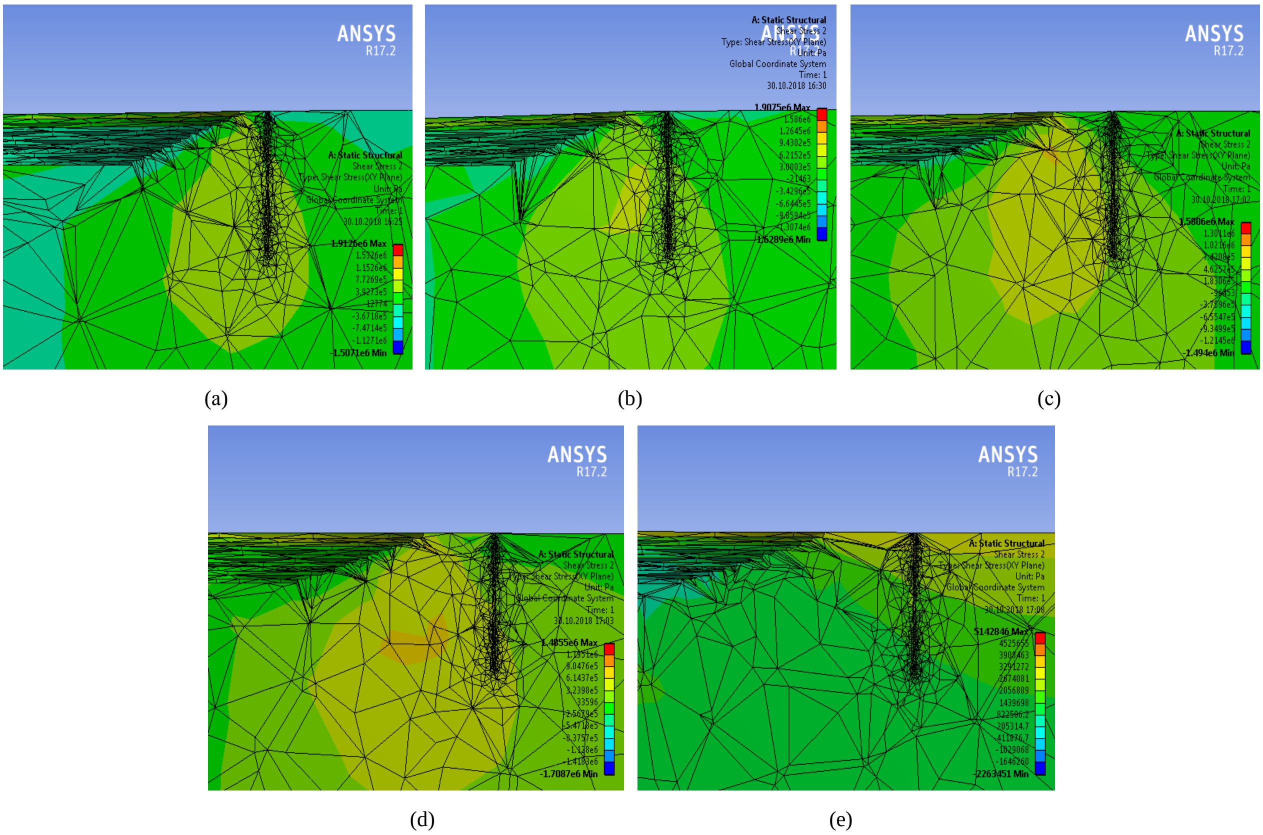


Figure 13. The stress-strain state of the massif near the shaft depending on the distance between the upper edge of the open-pit and the shaft (open pit depth is 200 m, section 4); The distance between the upper edge of the open-pit and the vertical shaft is: a)100 m; b) 150 m; c) 200 m; d) 250 m; e) 300 m.

As a result of modeling, the dynamics of changes in the zones and the values of active stresses depending on the depth of the open pit were obtained. The zones of high stress concentrations increase with increasing the open pit depth. From the obtained stress-strain state patterns of the massif, it is possible to obtain the graphs of changing stress σ depending on the depth of the studied points of the shaft.

The results of the numerical analysis make it possible to determine the stress values of the rock massif near the shaft. In the course of studies, at the distance of 50 m from the shaft at the depths of 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 350 m, 400 m, 450 m, 500 m, and 550 m from the earth's surface, the points under study were located (Figure 14). Changing of the stress values depending on the depth of the studied points are shown in Figures 15 to 24.

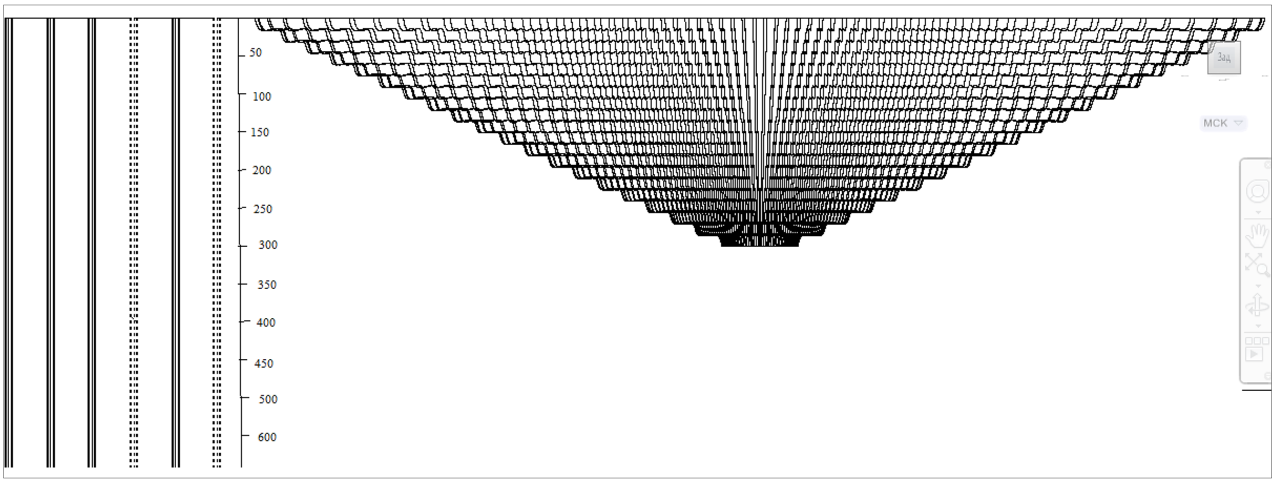


Figure 14. Location of the points under study

Figures 15 to 24 show the results of modeling the stress-strain state of the massif with variations in the depth of the open pit (100, 200, 300 m), as well as the distances from the upper edge of the open pit to the vertical shaft (100, 150, 200, 250, and 300 m).

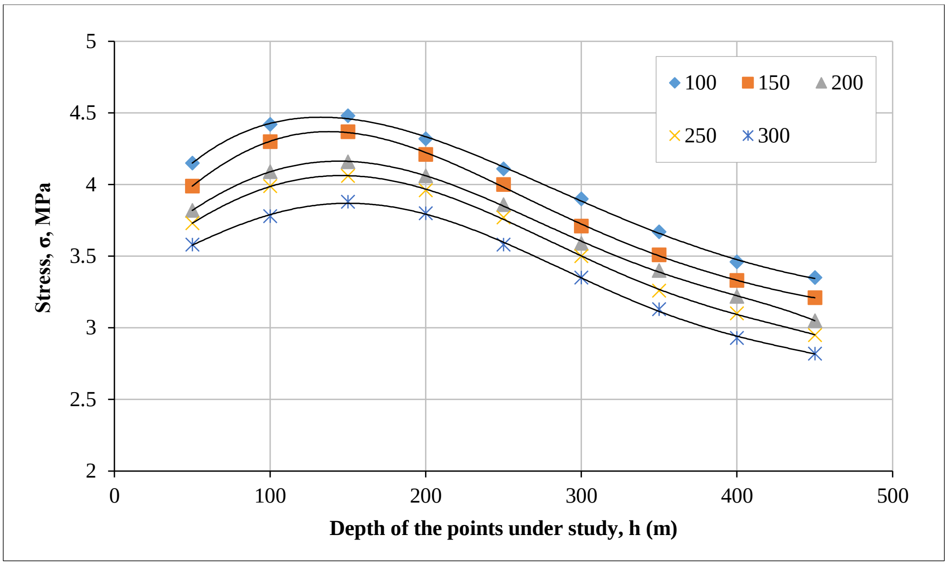


Figure 15. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 100 m, Section 2)

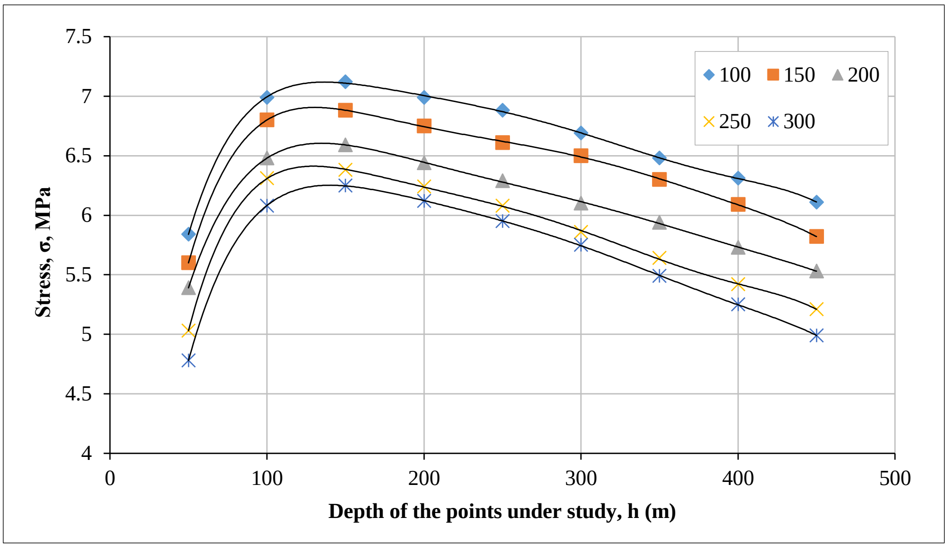


Figure 16. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 100 m, Section 4)

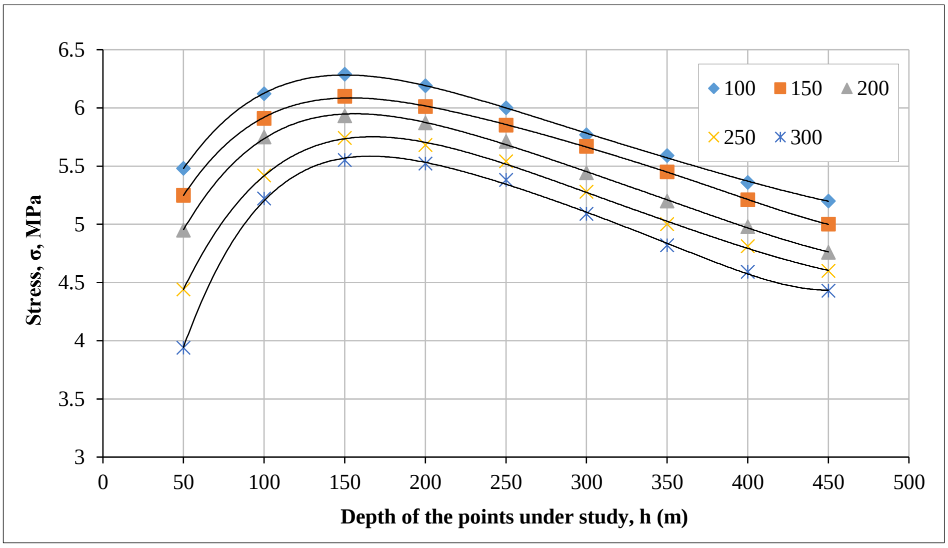


Figure 17. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 100 m, Section 3)

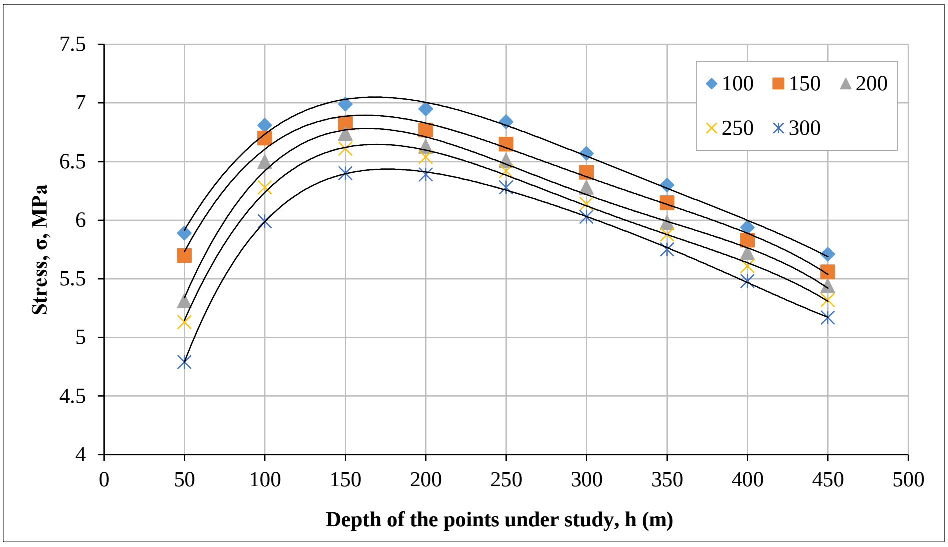


Figure 18. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 100 m, Section 5)

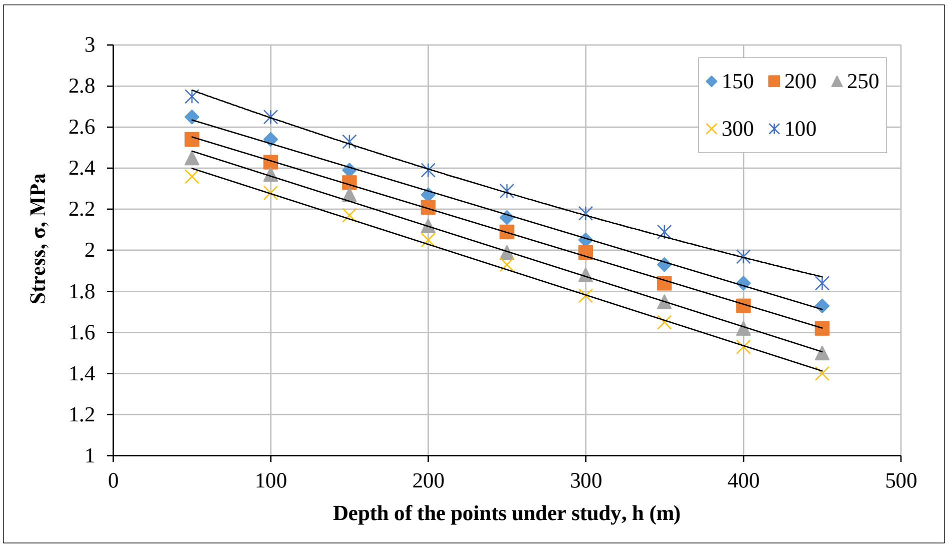


Figure 19. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 100 m, Section 1)

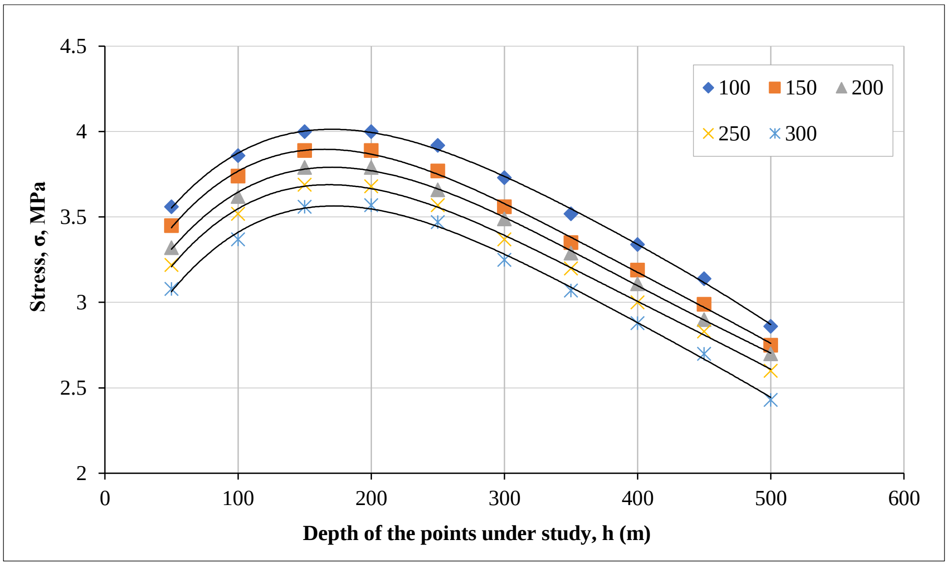


Figure 20. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 200 m, Section 2)

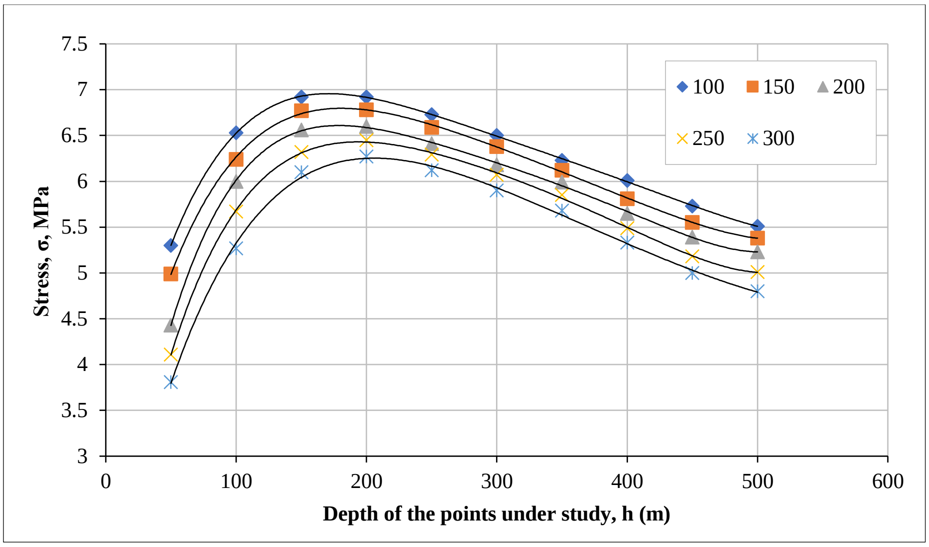


Figure 21. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 200 m, Section 4)

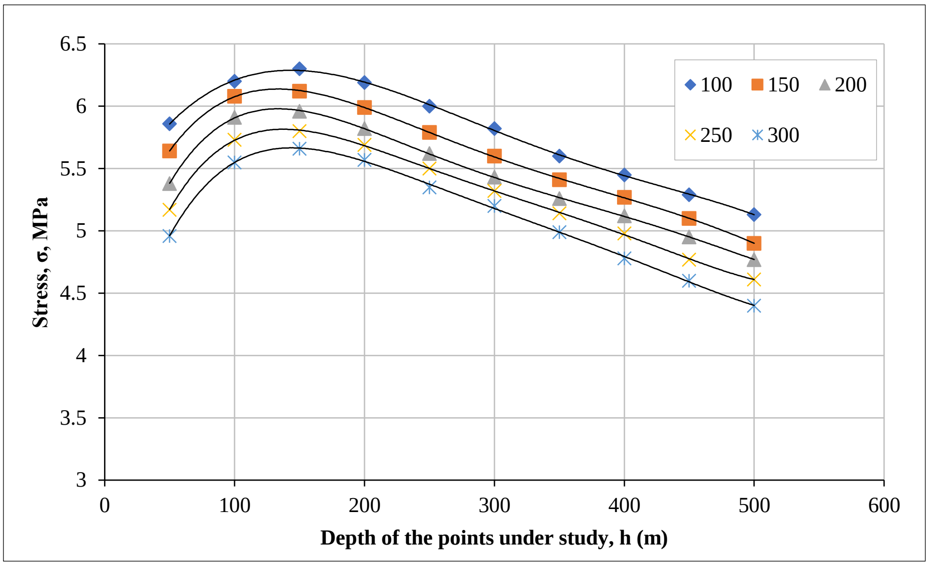


Figure 22. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 200 m, Section 3)

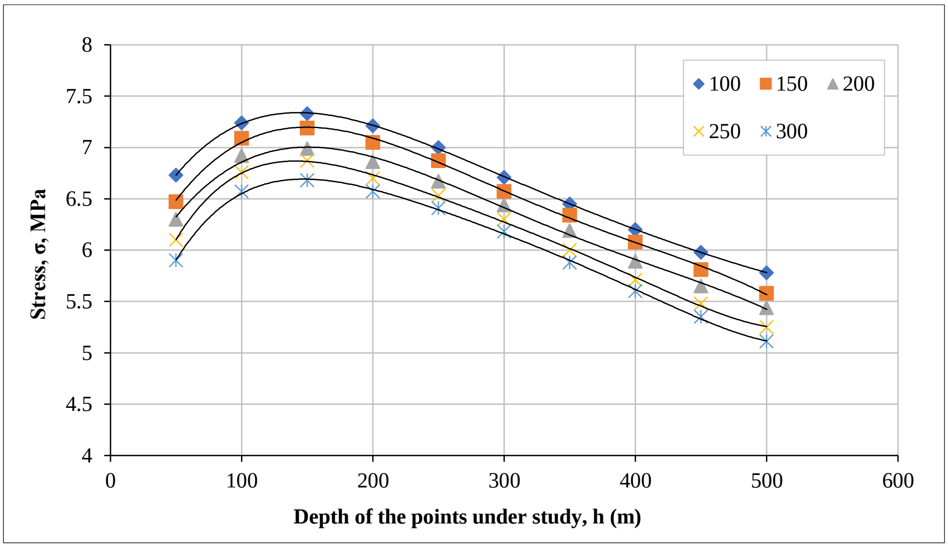


Figure 23. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 200 m, Section 5)

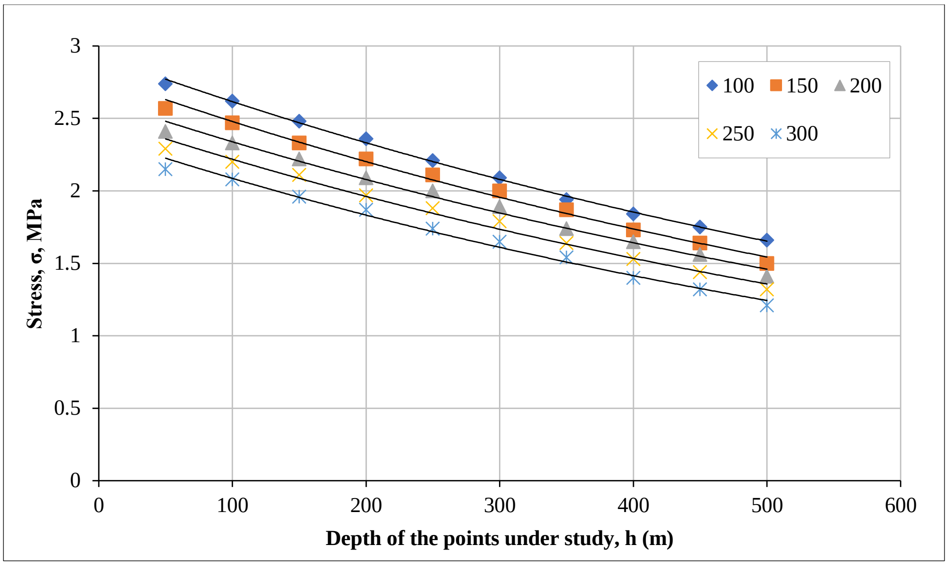


Figure 24. Graph of the dependence of stress values depending on the depth of the location of the points under study (at a depth of 200 m, Section 1)

The established stress dependencies at various measurement points along the depth of the shaft ʊ=φ(hst) allow an objective assessment of the minimum permissible distance of the shaft on the earth's surface from the edge of the open-pit. This approach to this parameter assessment allows to determine the most rational location of the shaft, which ensures long-term safe operation of the shaft during its entire service life in conditions of combined geotechnology.

In Figures 15 and 20, at the measurement depth of 50 m for an open pit with a depth of 100 and 200 m and with a radial direction of the open pit of 22.5 degrees, the minimum stress is 3.55 and 3.2 MPa, and then up to the depth of the studied point of 100 m, the stress increases and makes 4.4 and 3.9 MPa. At intervals of the studied points of 100-200 m, the stress remains within the range of 3.9 - 4.0 MPa; after the studied point of 200 m, there is observed smooth decreasing the stress. This phenomenon is caused by the fact that the peak stress is reached in the zone of maximum influence of the open working, in this case, at the depth of the point under study of 100-200 m. Then, as the location of the shaft moves away from the side of the open pit, the stresses are redistributed and reduced.

In Figure 19, with the pit depth of 100 m and in Figure 24, with the pit depth of 200 m, the radial direction with the angle of 0 degrees (in other words, along the long axis of the pit), the minimum stress at the test point of 50 m is 2.4 and 2.2 MPa, and the maximum stress is 2.8 and 2.8 MPa. At the depth of 500 m at the studied point, the minimum stress is 1.4 and 1.38 MPa, and the maximum stress is 1.9 and 1.75 MPa. A different picture is observed here: from the studied point of 50 m, a gradual decrease in stress is observed. This is caused by the fact that the lower end contour of the open pit is located at a relatively large distance from the shaft.

The stabilization of stresses in the interval from 200 to 350 m is explained by the simultaneous action of two contradictory factors: on the one hand, growth occurs with increasing depth; on the other hand, stress decreases due to the distance of the contour of the cone-shaped open-pit mining. Research results show that the minimum stress is at a distance of 300 m from the vertical shaft to the contour of the open-pit. The shaft location influences the capex for excavation, transportation, and other secondary works. The shaft location in combined mining should be determined based on the geometry of the open pit and distance to a shaft and the minimum possible distance for transporting ore and rock. In our case, this value is 100 m. Also, the results of numerical analysis show that in all cases the minimum stress is concentrated at a distance of 50 m from the contour of the open-pit mining with a different location of the vertical shaft relative to the open-pit.

Previously, a study was conducted for a round-shaped open-pit mine. The results of modeling the stress-strain state of the rock mass on nine models with a variation in the depth of the open-pit mining (200, 300, and 400 m), as well as the distances from the upper edge of the open-pit mining to the vertical shaft (100, 200, and 300 m), showed that [20] zones of high stress concentrations increase with increasing depth of the open-pit mining. At the depth of 50 m, for a 200 m deep open-pit mining, the minimum stress is 3.5 MPa, then an increase occurs according to the logarithmic law, reaching 6.4-6.6 MPa at a depth of 150-200 m. From a depth of 200 m, there is a gradual decrease to a value of 5.7 MPa. In general, in the range from 200 to 350 m, there is a slight decrease in stress, not exceeding a difference of 1 MPa.

As it is known, there are specific features of the formation of the stress-strain state of the rock mass in the combined mining system. On the one hand, a zone enclosed by potential sliding surfaces is formed near the sides of the open-pit mining; on the other hand, as a result of underground mining, a zone is enclosed in a subsidence area. Therefore, when choosing the location of the shafts, it is necessary to consider these factors.

4. Conclusion

The results of mathematical modeling for all the radial directions of the open pit show that the lowest stress is presented on the graphs in the radial direction with the angle of 0 degrees (see Figure 12). As noted above, the peak of the stress-strain state of the massif near the vertical shaft is achieved in the zone of maximum influence of the open pit space at the studied points from 100 to 200 m in depth. In this regard, when constructing a vertical mine shaft, it is necessary to pay attention to these stressed zones, since destruction and deformation of rocks around the vertical shaft can occur, and the shaft is needed to be secured to extend its serviceability. When selecting a safe location for the shaft, it is also necessary to take into account the surface topography, the groundwater, the heterogeneity of rocks, the surface structures, and objects.

The results of modeling the stress-strain state for an ellipsoidal open pit shape under combined development show that it is possible to solve effectively the issues of determining the area of the safe location of the main vertical mine shaft, taking into account the anthropogenic impact of the mined-out open pit space and the geomechanical state of the rocks in the near-pit zone in which the massif is subject to destruction. The main factors considered in the modeling are the physical and mechanical properties of the rocks, the depth of the open pit, and the distance of the shaft from the edge of the open-pit.

The results of research on the study of the stress-strain state of the rock mass along the line of vertical shafts near the open pit allow us to solve an important issue of determining the rational location of shafts, considering the impact of the open-pit. To assess more accurately the effectiveness of selecting the location of vertical mine shafts, it is necessary to take into consideration possible risks in making a technological decision.

5. Declarations

5.1. Author Contributions

Conceptualization, Sh.Z. and N.B.; methodology, Sh.Z. and A.I.; software, Sh.Z. and Ai.M.; validation, A.I, G.Y., and Az.M.; formal analysis, A.I.; investigation, N.B.; resources, G.Y.; data curation, Ai.M.; writing—original draft preparation, Sh.Z.; writing—review and editing, A.I.; visualization, N.B.; supervision, Az.M.; project administration, Sh.Z.; funding acquisition, A.I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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