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DETERMINING OPTIMAL BORDER PARAMETERS TO DESIGN A REUSED MINE WORKING

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ABSTRACT

Applying the methods of computational mathematics in terms of specific optimal operational indices of a reused mine working makes it possible to reduce resource intensity of the operations performed at that stage. However, the obtained results are hard to interpolate with respect to the whole mine working network. The problem is aggravated when mining and geological conditions of mine working drivage differ considerably within one and the same mine field. Grid methods of solution allow modeling peculiarities of a geomechanical model in a wide range; though, they have a set of features preventing from guaranteeing unambiguously the calculation quality. Field experiment, which is possible to carry out only after mine working drivage, is a standard practice to substantiate the efficiency of the developed technological solutions. In terms of the considered mining and engineering conditions, stress and strain of the geomechanical model components are to be measured throughout the mine working length. Consequently, it is possible to confirm the selection quality of support parameters of the mine working only when it is completely driven. In some cases, optimal indices may be obtained at the expense of changes in the mine working border shape; that requires considerable complication of the procedure to optimize computational models. The developed calculation methodology of calculation and performance of a field experiment has made it possible to implement the procedure of optimization of selecting the support for a reused mine working by comparing analysis of stress and strain state patterns for similar geomechanical models.

Keywords: mining, mathematical modelling, mine working design, rock mass fissility.

INTRODUCTION

Reduction of the mining prime cost depends immediately upon the level of the enterprise energy demands. Energy consumption stipulates investment attractiveness of not only the whole branch but also a specific mining enterprise. During the mining process, all the production chains are equally energy-intensive; thus, reduction of energy consumption becomes an extremely important factor while organizing any type of activities [1-3]. It is clear that different mining and geological conditions require their application of specific technological solutions ensuring possible operation of the deposit being developed [4–6]. Drivage and support of the mine workings should guarantee safe development of the deposit as well as provide minimal acceptable level of the production costs both physically and financially [7]. Optimal conditions of mine workings driving and supporting make it possible to minimize energy consumption, reduce material consumption of the production and decrease overhead costs simultaneously [8, 9]. Reusable mine workings as a technological solution allows reducing considerably the required driving operations [10]. However, support of those mine workings is a complex technical task due to wide range of external factors effecting a geomechanical system [11–13].

Nowadays, designing of underground construction often involves numerical methods to model various mining-engineering objects [14]. Possibility to model geometrically complex computational region, solution of various-definition problems of mining mechanics taking into account factors of component damage of computational model, and changes in physical properties of the materials with time are positive features of such a methodology [15].

MATERIALS AND METHODS

Computational model generated while analyzing the state of geomechanical system of the reused mine working has become a basis for the research [9, 16, 17]. The model makes it possible to be very accurate while describing all the effect of the enclosing medium upon separate element of the computational model.

Calculations of the computational experiment were performed involving a finite element method. A problem of geomechanics was formulated taking into consideration the factors of rock softening and rheology. Computational region was developed geometrically in the form of a volumetric model with full-body modeling of all the components of a support system. Region size as well as boundary and initial conditions were formed according to the principles stated in a multimetric recursive model [18, 19]. The technique makes it possible to select the parameters of geomechanical system being critically important for the computational process as well as to determine their description type. That provides high accuracy of the performed calculations along with minimization of the costs for both computational experiment and procedures to control mine working conditions during its operation [20, 21].

Tables of deformations and stresses at the selected computational points are given as the results of the computational experiments being analyzed. Data arrays were processed to detect the points having special characteristics which analysis makes it possible to draw firm conclusions on the processes taking place in a geomechanical system [22]. Supporting points were selected to compare the results of the computational experiment and field measurements along the mine working border. Deformations within those points were used as the initial data to construct spline interpolation of the reused mine working border.

Complex criteria to evaluate stress and strain state of a geomechanical system were used while determining optimal combination of a support system and border of the mine working being designed. A set of the criteria was determined while performing computational experiments on the effect of various elements of the computational region upon separate elements of a geomechanical system [23]. A key parameter being the most determinant in terms of state changes was define for each specific element in the context of specific external factors.

Thus, the initial stage of the parameters optimization of a reused mine working being designed involves the development of a computational region providing stable mathematical convergence of the performed calculations taking into consideration the selected critically important elements to describe states and processes of geomechanical system changes. The obtained values are adapted to the conditions of field measurement performance that guarantees their unambiguous interpretation while carrying out further analysis.

RESULTS

In terms of G.G. Kapustin mine, consideration of fissility of the border rock mass is the main problem while designing and driving mine workings. The mine has certain areas with different characteristics of fissure systems and water-content degree; that effects the selection of characteristics for the support system and safety of mine workings, especially of those being subject to repeated use. Optimal conditions to provide those mine workings stability requires developing a geomechanical model of the border rock mass behaviour which will consider not only the whole range of its nonlinear mechanical characteristics but also ensures proper interpretation of mutual rock-mass and support-component effect.

The developed model was tested for its adequacy in terms of 75 belt entry of G.G. Kapustin mine by setting four measuring stations to evaluate the state of a reused mine working along its border. All the measuring stations were mounted in terms of various mining and geological conditions throughout the entry length.

Measuring stations included following components: tension sensors (they were fixed on the anchor bodies mounted in the rock mass and used to measure stresses in anchors after their mounting); laser ranger (used as a sensor of vertical convergence of rocks within the roof and floor of a mine working, the measurements helped compare the results of current and previous studies) [24, 25]; and light-reflecting anchors (used mechanisms of photometry and spline interpolation to obtain a shape of the whole mine-working border deformation) [26].

First measuring station was mounted at a site with clear one or two systems of fissures with insignificant water inflow. Second measuring station was located in terms of similar conditions but with ternary fissure system. There were 347.3 m between the stations. Stations three and four were set in terms of increased water content of the rocks of border mass; third station was within the zone of the effect of two fissure systems while the fourth one was within the effect of three fissure systems. Distance between those stations was 172 m.

Objective of field measurements was to prove the efficiency of the obtained computational model with following interpolation of its results with respect to the conditions of determining the character of the behaviour of different support systems in terms of the reused mine working. In terms of that particular case, it was required to prove peculiarities of deformation of mine working border obtained while carrying out a computational experiment to be the basis for further selection of optimal mine working cross-section.

The obtained field observations of changes in the mine working border were divided into two groups according to their features. First group included the measurements performed outside the zone of increased water-content effect; second one included the measurements performed within the zone of that effect. Calculations involving multiparametric nonlinear recursive models of computational experiment performance were carried out according to mining and geological conditions of those groups. Calculations were carried out not only to prove the efficiency of the support of the available entry but also to determined optimal engineering solution providing increased stability of the reused mine working under conditions of fissility and water content of the border rock mass.

Figure-1 demonstrates the first set of the obtained values. Correspondingly, Tables 1-3 show data sampling being the basis to construct those diagrams.

VOL. 15, NO. 24, DECEMBER 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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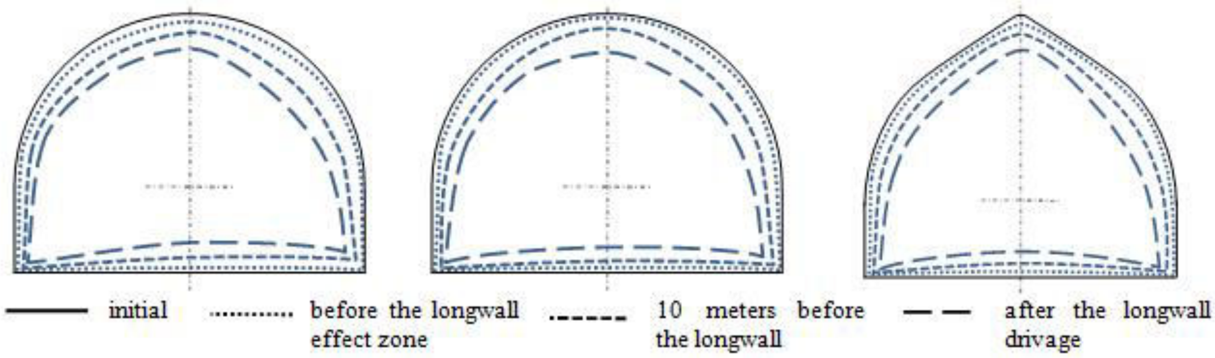

Figure-1. Changes in the border of a reused mine working obtained in terms of the developed fissure systems as a result of: a) field measurements; b) performed calculations; and c) calculations for KBT-2 support.

While comparing Figure-1a and Figure-1b, a qualitative difference in the formation of mine working roof as a result of measurements and performed calculations is seen as once. If both qualitative and quantitative deviations within the walls and floor of the mine working are not more than 5 - 12%, then the deformation shape, rate, and value of the mine working differ considerably. Quantitative deviations have exceeded 21% of average level of the border deformation within a specific site of the mine working roof, towards a stoping face.

In this context, while calculating, deformation of the mine working border turned out to be more symmetric than the averaged measuring index in terms of two stations. Final difference of cross-section areas while calculating and measuring was less than 14% making it possible to tell about almost the same dissipation level of the internal deformation energy of a “rock mass - mine working support” system.

Finally, having compared Figure-1, b and Figure-1, c, it is possible to predict probable behaviour of KBT-1 support under the considered mining and geological conditions. First, in terms of KBT-2, value of the predicted deformations of the mine working border will be less by 8% on average, than in terms of KMP-A3 support. Moreover, taking into account a resulting border and comparing it with others represented in Figure-1, it is possible to make a conclusion on more stable state of the mine working roof, if KBT-2 is applied.

Table-1. Deformation of mine working border in terms of mine conditions.

Control point	Displacements, recorded under natural conditions, mm					
	before the longwall effect zone		10 m before the longwall		after the longwall drivage	
	X	Y	X	Y	X	Y
1	28	33	132	146	187	288
2	-48	52	-127	161	-346	342
3	23	14	99	182	162	259
4	-18	16	-142	169	-344	387
5	6	-29	58	-104	67	-212
6	-8	-33	-28	-167	-122	-234

While analyzing the data of Tables 1 and 2, conclusions should be made on the fact that changes in the state of deformed mine working border during stoping advance are in accordance with one and the same law. Consequently, the selected calculation model interprets time changes in states of the border rock mass in the right way.

Table-2. Deformation of mine working border obtained during calculations.

Control point	Displacements, obtained during calculations, mm					
	before the longwall effect zone		10 m before the longwall		after the longwall drivage	
	X	Y	X	Y	X	Y
1	14	18	102	98	175	318
2	-14	18	-154	137	-312	359
3	18	12	120	238	154	302
4	-18	12	-145	189	-297	366
5	12	-28	50	-124	89	-199
6	-12	-30	-59	-121	-98	-201

The conclusions are based on two key features of the obtained results. Firstly, Figure-1, c shows that changes in the mine working border relative to vertical axis are symmetric contrary to the borders in Figure-1, a and Figure-1, b indicating relatively low torques within the frame support component; secondly, maximum displacements of KBT-2 support are by 9 - 11% less than in case of circular roof. That provides preserving the operational characteristics of the reused mine working for much longer period of time as well as the reduced energy intensity for its maintenance.

Table-3. Deformations of mine working border obtained during calculations for KBT-2 support.

Control point	Displacement, obtained during calculations for KBT-2 support, mm					
	before the longwall effect zone		10 m before the longwall		after the longwall drivage	
	X	Y	X	Y	X	Y
1	18	17	57	62	241	243
2	-18	17	-105	138	-245	216
3	16	18	134	126	248	254
4	-16	19	-127	193	-298	327
5	14	-32	49	-104	70	-186
6	-14	-31	-56	-101	-75	-186

Table-2 contains calculations and measurements performed under conditions of increased water content of the rock mass. Tables 4 - 6 demonstrate the data being the basis for the diagrams being considered. Use the procedure applied while examining Figure-1. to analyze the data.

It is clearly seen that the available water content has resulted in absolute growth of mine working border deformations as well as in the increased symmetry level of a resulting border. Moreover, the regularity is observed within all the three schemes of Figure-2. That demonstrates the adequacy of the selected model for representing water content of the border rock mass. Apart from that, final areas of the mine working cross-sections for variants a and b (see Figure-2) practically coincide; the difference is less than 4%.

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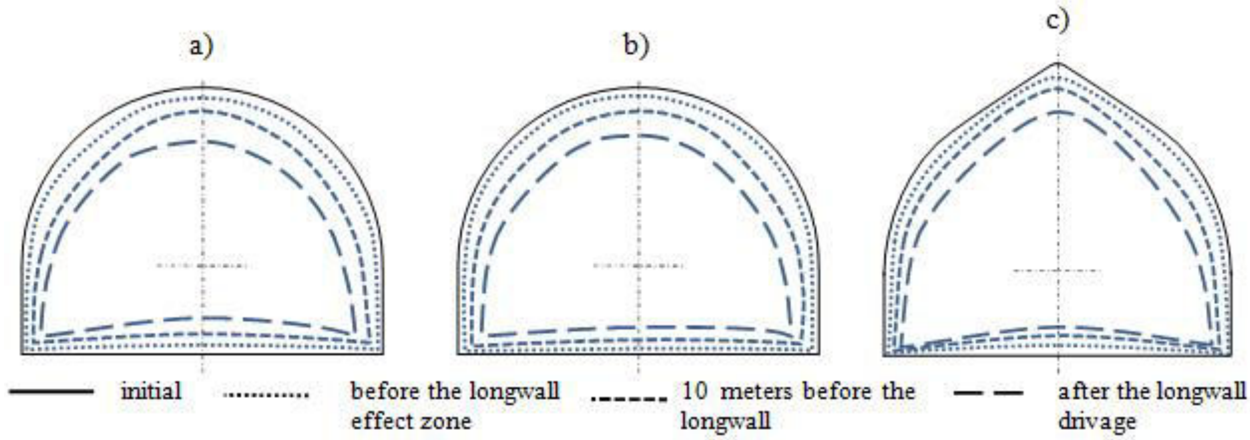

Figure-2. Changes in the border of a reused mine working obtained in terms of the increased water content as a result of: a) field measurements; b) performed calculations; and c) calculations for KBT-2 support.

It should be also noted that the shapes of final cross-sections represented in Figure-1, c and Figure-2, c do not differ qualitatively while quantitative deviations are characterized by the same order and value as Figure-1, a - Figure-2, a and Figure-1, b - Figure-2, b pairs. That makes it possible to draw conclusions on the retained efficiency of the selection of mine working cross-section even in terms of the available high level of water content of the border rock mass.

Changes in the mine working border are also characterized by the development of several areas of fluctuation relative to the deformation rate. That is the result of decrease in the value of tangential stresses within the border rock mass owing to the increase in the rock anisotropy. There is redistribution of deformations with their absolute increase along the mine working border due to nonlinear deformation of a significant share of the border rock mass.

According to the data of Tables 5 and 6, water content of the rock mass results in the fact that the tent-shaped cross-section has distinct advantage comparing to the circular one. The obtained pattern of deformations indicates clearly the decrease by 3 - 5% of full movements of the mine working border points. It means that the effect of water content was reduced by about 10% owing to a new formula of the mine working border.

Table-4. Deformation of the mine working border in terms of mine conditions.

Control point	Displacements recorded during field measurement, mm					
	before the longwall effect zone		10 m before the longwall		after the longwall drivage	
	X	Y	X	Y	X	Y
1	42	64	178	143	304	393
2	-41	59	-153	116	-367	386
3	36	56	194	183	302	317
4	-33	49	-217	241	-334	325
5	24	-38	96	-117	145	-162
6	-28	-43	-103	-127	-211	-289

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Table-5. Displacements obtained during calculations.

Control point	**Displacements obtained during calculations, mm**					
	before the longwall effect zone		**10 m before the longwall**		**after the longwall drivage**	
	X	Y	X	Y	X	Y
1	38	37	165	152	325	369
2	-41	44	-138	131	-349	371
3	24	30	149	157	341	322
4	-27	32	-195	163	-348	302
5	16	-20	49	-125	140	-178
6	-19	-22	-84	-137	-192	-274

Table-6. Deformations of the mine working border obtained during calculations for KBT-2 support.

Control point	**Displacements obtained during calculations for KBT-2 support, mm**					
	before the longwall effect zone		**10 m before the longwall**		**after the longwall drivage**	
	X	Y	X	Y	X	Y
1	42	33	134	196	302	311
2	-37	40	-258	216	-354	352
3	18	25	96	104	298	296
4	-23	28	-174	177	-305	342
5	22	-23	141	-108	176	-134
6	-21	-23	-129	-111	-168	-137

Thus, the selected parameters of the computational model have provided sufficient calculation and physical accuracy of the obtained results within the range of 15% that have been achieved by application of miltiparametric nonlinear cursive model of computational experimentation [27].

Modeling of rock mass fissility involving multiparametric nonlinear recursive model in terms of Krasny Partizan mine has demonstrated the possibility to use one calculation for the cases of one, two, and three fissure systems while predicting the border deformation. The calculation itself was performed taking into consideration three fissure systems.

Figure-3 demonstrates calculation results for different support types comparing to field measurements. Comparison of field measurements and calculated indices of KMP-A3 support shows high accuracy of the obtained graphs convergence. Despite the qualitative deviations, in terms of quantity, value difference has the maximum of 37 mm at the moment when face plane passes the cross-section plane of the first station. However, peculiarity of the calculated graph in terms of bench formation within the area of 50 m behind the longwall is rather disturbing (see Figure-3). In the context of the considered graph, nature of that feature of the computational experiment is not possible to be evaluated but it will be examined while analyzing following graphs.

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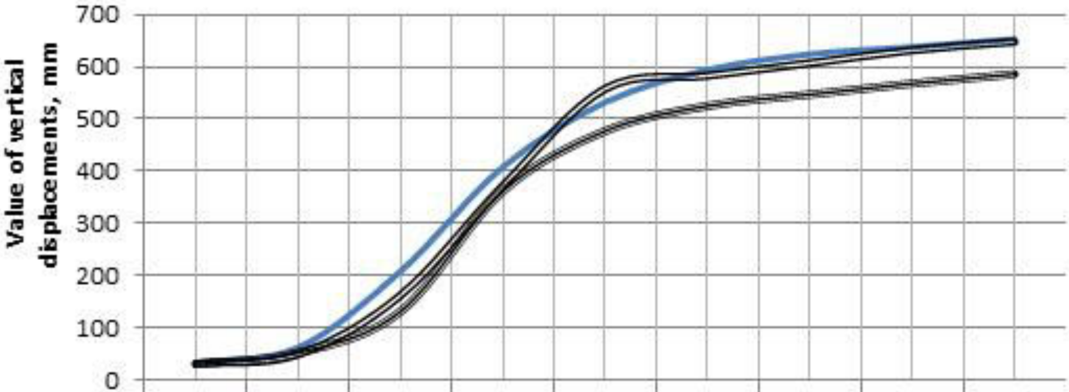
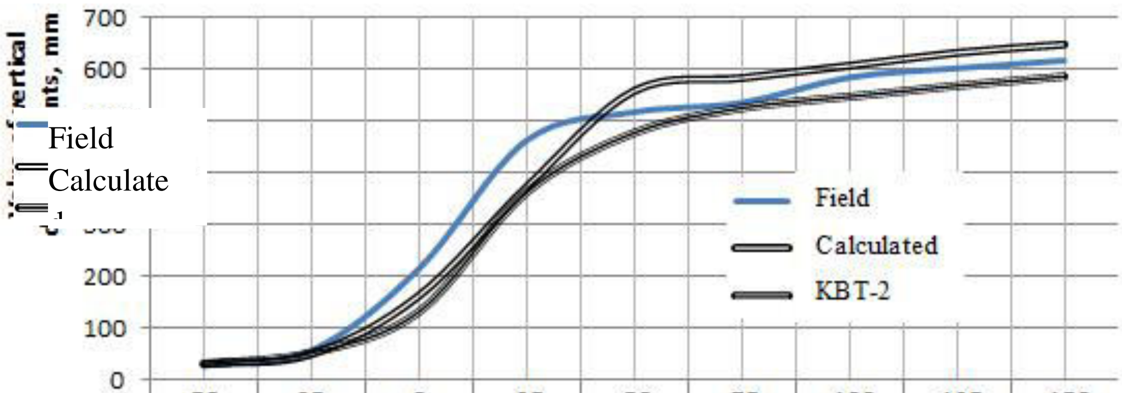
ARPN Journal of Engineering and Applied Sciences



Longwall advance, m	50	25	0	-25	-50	-75	-100	-125	-150
Field	32	62	208	408	532	594	624	638	653
Calculated	31	49	162	372	558	583	607	632	648
KBT-2	30	52	131	362	477	525	547	568	586

Figure-3. Vertical displacements of the roof and floor rocks of the reused mine working in terms of first measuring station with the prevailing two fissure systems.

As for the calculation of KBT-2 support, it should be concluded that the calculation corresponds qualitatively mostly to the field measurements than to the calculations for KMP-A3 support. Quantitative indices show the increase with time of a tent-shaped support resistance relative to the support of circular cross-section by up to 14%; that influences considerably the stability of the reused entry behind the zone of the increased rock pressure effect [28].



Longwall advance, m	50	25	0	-25	-50	-75	-100	-125	-150
Field	27	56	214	462	517	535	584	602	617
Calculated	31	49	162	372	558	583	607	632	648
KBT-2	30	52	131	362	477	525	547	568	586

Figure-4. Vertical displacements of the roof and floor rocks of the reused mine working in terms of first measuring station with three fissure systems.

While considering the graphs shown in Figure-4, it is easy to find qualitative changes in the results of field measurements performed in terms of second measuring station comparing to the first one. Now, measurement graph contains a bench similar to the graph of calculation results. The bench reduces significantly qualitative correspondence of the considered graphs. Suffice to say that the difference in the values of displacement of mine working roof and floor reaches 90 mm in absolute indices. Available SSS effect of a "rock mass - mine working support" system of the third fissure system is the obvious fact influencing the measuring results. Thus, the reason

VOL. 15, NO. 24, DECEMBER 2020 ISSN 1819-6608
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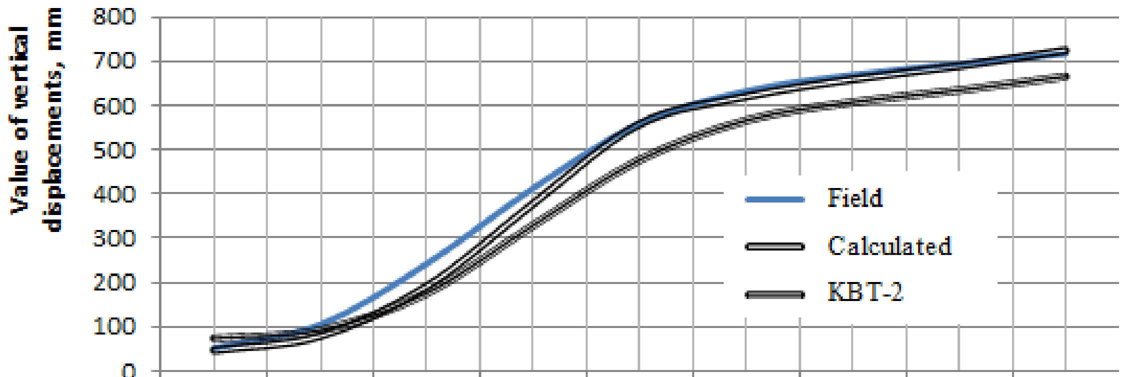
why the graph in Figure-3 contains the bench is rather clear: initially the calculations were performed taking into consideration all the fissure systems available within the rock mass being modeled. The bench displacement relative to the calculation is caused by not considering the rock mass anisotropy; in this very case, that has resulted in significant redistribution of deformations from vertical to horizontal plane.

Consequently, analysis of Figure-3 and 4 graphs results following conclusion: use of a tent-shaped support makes in possible not only to reduce of vertical rock convergence into the mine working but also to provide levelling of the effect of fissure systems (oriented in different ways towards longitudinal axis of the mine working) upon the mine working frame support.

Figure-5 represents graphs of measurements and calculations performed for the conditions of increased water content of the rock mass weakened by two fissure systems.



	50	25	0	-25	-50	-75	-100	-125	-150
Field	52	105	242	413	559	632	669	694	716
Calculated	47	79	191	378	558	620	659	689	724
KBT-2	74	92	176	329	477	566	607	634	665

Longwall advance, m

Figure-5. Vertical displacements of roof and floor rocks of the reused mine working in terms of the first measuring station with the prevailing two fissure systems and high water-content degree.

As it is seen, both qualitative and quantitative indices of the graphs are of high convergence level not requiring significant comparative analysis; maximum deviation is 51 mm. Thus, the computational region obtained by means of multiparametric nonlinear recursive model has demonstrated high level of adequacy expressed in the available deviations being more than 10% only within a third share of all the measurements. In this context, absolute deviation is not more than 20%.

In terms of field measurements (Figure-6) performed under the effect of all the three fissure systems, qualitative pattern and the calculated data are slightly different again caused by the effect considered earlier. However, in terms of quantity, absolute deviations are only 44 mm indicating the fact that measurement and calculation results differ only within 13%. Apart from that, a comparison, which takes into account water content or its nonavailability, involves a strict difference towards the growth of the deformations of the first variant over the second one by 94 - 115 mm on average.

In the context of all the calculations, vertical deformation values of the reused mine working in terms of KBT-2 support up to the entering the increased rock pressure zone are almost the same to the deformations for KMP-A3 support. When stoping face is driven through the plane of mine working cross-section, where measuring station is mounted, vertical displacement of the enclosing rocks decreases by 97 mm on average, if KBT-2 support is used. That indicates relatively low effect of water content of the border rock mass upon the deformation degree of the reused mine working border under considered mining and geological conditions. Here it should be noted that if the rocks are water-cut, then vertical deformation gradient of the mine working grows at lower rates than in terms of insignificant watering.

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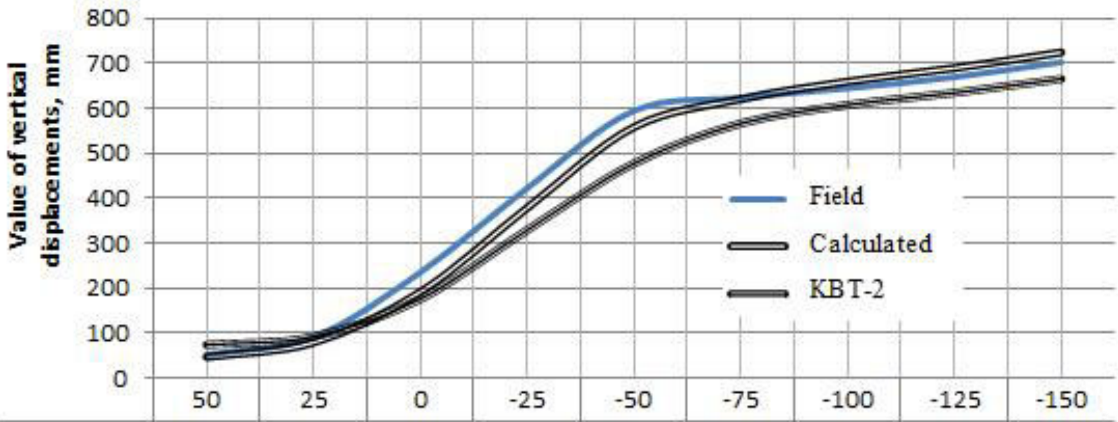

	50	25	0	-25	-50	-75	-100	-125	-150
Field	52	91	235	422	594	623	644	669	702
Calculated	47	79	191	378	558	620	659	689	724
KBT-2	74	92	176	329	477	566	607	634	665

Figure-6. Vertical displacements of roof and floor rocks of the reused mine working in terms of the first measuring station with three fissure and high water-content degree.

In general, the obtained results of the analysis of calculated values and deformation stress values measured experimentally in mines demonstrate high degree of adequacy both in qualitative and quantitative indices. The applied computational model helps describe the whole range of physical phenomena and states characterizing geomechanical system of the reused mine working being operated under various mining and engineering conditions. A technique to develop computational model makes it possible to implement procedures of support system optimization as well as the border shape of the designed mine working basing upon the results of calculations performed with the consideration of alternating stability, water content, and fissility of the rock mass.

CONCLUSIONS

The applied methodology to study stress and strain state of a geomechanical system of the reused mine working helps determine optimal indices of a support system consisting of various-type components right at the stage of designing. The methodology makes it possible to define different types of rock mass borders to improve operational characteristics of mine workings. Moreover, the technique allows decreasing limit state zones of the rocks and changing their location to reduce considerably the level of effect upon the support system components. The optimization helps considering the whole range of geomechanical model characteristic as well as predicts changes in mine working border with time. A field experiment ensures calculation efficiency of the computational model, proves calculation quality, and interpolates the control parameters for the obtained results in terms of changing in certain elements of a computational region.

Complex analysis of stresses and strains possible within the geochemical system components allows defining the character of rock mass effect upon the mine working support; that helps determine a necessity degree and quality level for the description of a specific computational region parameter. A model optimized in such a way is somehow universal within the frameworks of certain combinations of both mining-geological and engineering parameters. Being formed once, a border to control calculations may be used while optimizing parameters of the reused mine workings without additional clarification of the computational model. In this context, optimization process may come either from the internal parameters of a computational region or from the external ones basing upon the features of the problem under consideration. That provides algorithmization of the decision-making processes; as a result, that reduces costs to design certain mine working by 10 - 12%.

ACKNOWLEDGEMENTS

The study has been carried out within the framework of research project of the NAS of Ukraine for young scientists “Resource-saving techniques to support mine workings under the complex hydrogeological conditions”; Agreement #29-04/06-2020; official registration # 0119U102370.

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