Predicting the producing well stability in the place of its curving at the underground coal seams gasification

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Abstract. The relevant issues have been studied of ensuring the stability of producing wells in the place of their curving when uncovering the mining extracted area for the underground gas generator operation. It is emphasized that the design planning of efficient operation of underground gas generators in downhole gasification technology is impossible without consideration of the stress state of the rock massif, which can lead to a danger of the wellbore cutting and emergency shutdown of the technological system operation. The parameters of geomechanical models have been developed and substantiated for the study of the stress state of the "rock massif – producing well" system under the conditions of the Lviv-Volyn coal basin. A computer simulation has been performed of change in the stress state of a laminal massif around a well with a curvature radius in the range of 5 – 25 m with the use of the finite element method. The exponential function has been revealed of the tensile stresses value in the roof of the seam from the angle of the producing well entry into the coal seam. It is recommended the rational angle of a well entry into the coal seam, which is in the range of 21 – 28 degrees, and an appropriate curvature radius will be 5 – 10 m.

1 Introduction

Coal is the main strategic fuel and energy resource of Ukraine, which is able to ensure the development of leading industries for the next centuries. The hardcoal reserves, as of 01.01.2018, are estimated at 41.9 billion tons for categories $A+B+C_1$ and 11.23 billion tons for category C_2 [1]. Despite the significant coal reserves, their extraction over time becomes more labour-consuming and cost-intensive, due to the complex mining and geological conditions of their occurrence [2, 3]. These are, first of all, insignificant thickness of seams, low stability of the host rocks, considerable depth of the seams bedding, gas content, water-cut and other factors [4, 5]. The coal mined in such conditions becomes uncompetitive as its production cost may exceed its selling price [6].

To ensure the energy self-sufficiency of Ukraine, leading scientists of the country are trying to search for alternative technologies for the development of hydrocarbon energy resources, such as natural gas hydrate fields [7 – 10], and methane reserves in the mine fields

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of operating mining enterprises [12, 13]. In world practice, in the countries with significant coal reserves, an underground coal gasification has become widespread as an alternative technology to traditional mechanized coal mining [14 – 16]. The underground coal gasification has become widespread in advanced developed countries like China, USA, Poland, Republic of South Africa, Australia, etc. [17, 18]. As a result of the gasification process, the valuable energy and chemical products are the final products [19, 20], and by controlling the process parameters, their different concentrations and compounds can be obtained depending on market conditions [21, 22]. An undeniable advantage of underground coal gasification technology is the absence of industrial waste as a result of mining operations, unlike the traditional development technologies, the use of which forms on the daylight surface numerous mine rock accumulations in dumps [23 – 25]. These mine rock accumulations, with sufficient feasibility study, can be partially placed in the underground space by means of the technology of backfilling the mined-out space [26 – 27].

When developing the coal seams areas by underground gasification, it is necessary to predict the stability of the main elements of the technological scheme – blast injection holes and gas outlet wells, the period of existence of which is equal to the period of mining the coal seams areas by an underground gas generator and can reach up to six months. The stable operation of gasification technology depends on the state of main wells, which are laid for a long period of time. Without considering the peculiarities of the stress-strain state of rock massif, the deformation of rocks around the wells can lead to loss of its wellbore caused by cutting and creating an emergency situation with the subsequent shutdown of the underground gas generator.

As foreign and domestic experience of underground coal gasification indicates, most often the preparation of underground gas generators is conducted by drilling the vertically inclined producing wells [29, 30]. In this case, when producing wells enters the coal seam, a certain their curvature radius should be observed, and in this area of the wells there is a risk of increased stress concentrations. At the present time, the leading scientists have performed a lot of research into the field of improving the technological schemes of gasification, upgrading the quality of gasification products and the stability of the process itself, as well as the formation of the stress-strain state of rocks in the course of underground gasification [31 – 34]. The performed studies dealt mainly with the state of massif around underground gas generators, but there is not enough attention in literary and informational sources to the accounting of geomechanical factors and predicting the stability of producing wells, especially in the area of their curvature - as an important technology element.

Therefore, it is necessary to study the stress state of a laminal massif enclosing a producing well under the conditions of mining very thin and thin coal seams by means of underground gasification.

2 The choice of object to study

The prediction of the producing wells stability in the technology of underground coal gasification is supposed to be made in mines that develop thin and very thin coal seams. The enterprises are preferable that develop the seams with low thickness in difficult mining and geological conditions. In terms of location, the coal reserves are available in the Donetsk and Lviv-Volyn coal basins.

The Western Donbas is the youngest region of the Donetsk Basin. In this region, the coal reserves are mined by the five mine departments of the company PJSC "DTEK Pavlohradvuhillia". These subunits have several advantages over other coal-mining enterprises of Ukraine thanks to the modern system of production management, a high level of mechanization of stope and preparatory works, and significant geological coal reserves. In the conditions of the Western Donbas mines, an increase is observed in the level of stope

works, the load on the stope face was 2 – 2.5 thousand tons per day from one longwall face, and in some cases 4.4 – 4.5 thousand tons per day [35]. However, on the territory of the Lviv-Volyn coal basin, there has been a tendency for a decline of hard coal production performance over last ten years (Fig. 1), which leads to social and economic perturbations.
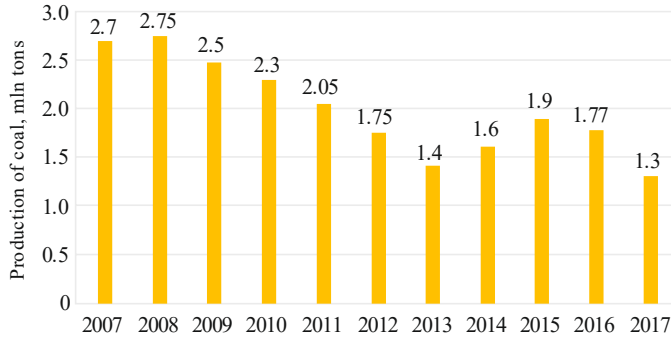

Fig. 1. The production of coal by mines of the SC Lvivvuhillia in 2007 – 2017.

Lviv-Volyn coal basin is the main fuel and energy sector of the western part of Ukraine. The political, socio-economic and environmental factors make a great influence on the choice of directions for the coal industry development in the Western Ukraine.

In order to avoid this situation, it is possible to restructure the coal industry and introduce new economically and environmentally friendly technologies for mining this mineral. In spite of the unprofitability of coal enterprises in the Lviv-Volyn coal basin, the strategic national interests condition the necessity of their preservation as part of the fuel and energy sector of Ukraine. For more efficient development of the Lviv-Volyn coal basin, it is necessary to rehabilitate and modernize the technological schemes of coal mining. That is why, these studies have been made in order to provide the Western Ukraine with energy raw materials, obtained as a result of gasification.

As an object of study, a mine field area of mine "Velykomostivska" of the Lviv-Volyn coal basin has been chosen, which is assigned to losses and is suggested by the authors for developing the underground gasification. The study of the stress state of rocks around the stope and preparatory mine workings at the traditional technology of coal mining in the Lviv-Volyn coal basin is described in the work [36]. However, during the underground coal gasification, the stress state of rocks containing wells was not studied.

The coal seams n_7^b, n_7, n_7^t, n_8, n_8^t, n_9 are of major industrial importance, the thickness of which varies from 0.6 to 1.8 m, the thickness of interstratal rocks – from 3.6 to 28 m with a slope angle up to 5º. These coal seams are concentrated in the geological worlds and are related to the class of contiguous coal seams, where their development influences significantly on the mining operations efficiency. They have both a simple one-patch structure and a complex one when the layer consists of two, three or more coal patches separated by rock layers. In the coal seams structure, a significant place is occupied by sapropelithes, which are interbedded with humic or coal seams, occurring in their bottom and roof. The rock layers of seams consist mainly of carbon-bearing argillites and siltstones.

3 Research methods

In the work, the preparation of a gas generator through the n_7^b seam is supposed, since the development of the seams with greater thickness by underground gasification is the most rational for efficient and stable obtaining the final energy product. To conduct the study, the northern area was chosen of mine "Velykomostivska" SC "Lvivvuhillia",

through the $n_7{}^b$ seam – "Sokalskyi". The $n_7{}^b$ seam – "Sokalskyi" is the lower commercial seam. The $n_7{}^b$ seam balance reserves have been mainly mined out. An insignificant amount of reserves remained in certain areas of the southern and northern flanks and near the main mine workings of directions. The seam has simple structure; its thickness is 1.00 – 1.45 m. Lithologically, it is represented by the upper humic patch and by the lower sapropelic. The roof is argillite; the bottom is siltstone. The depth of the seam occurrence ranges from 423 m in the eastern part of the mine field to 482 m in the western part of the mine field. The structural sections of the $n_7{}^b$ seam along the northern and southern mine flanks, as well as the selected area of the seam, where the wells stability is studied, are represented in Fig. 2.
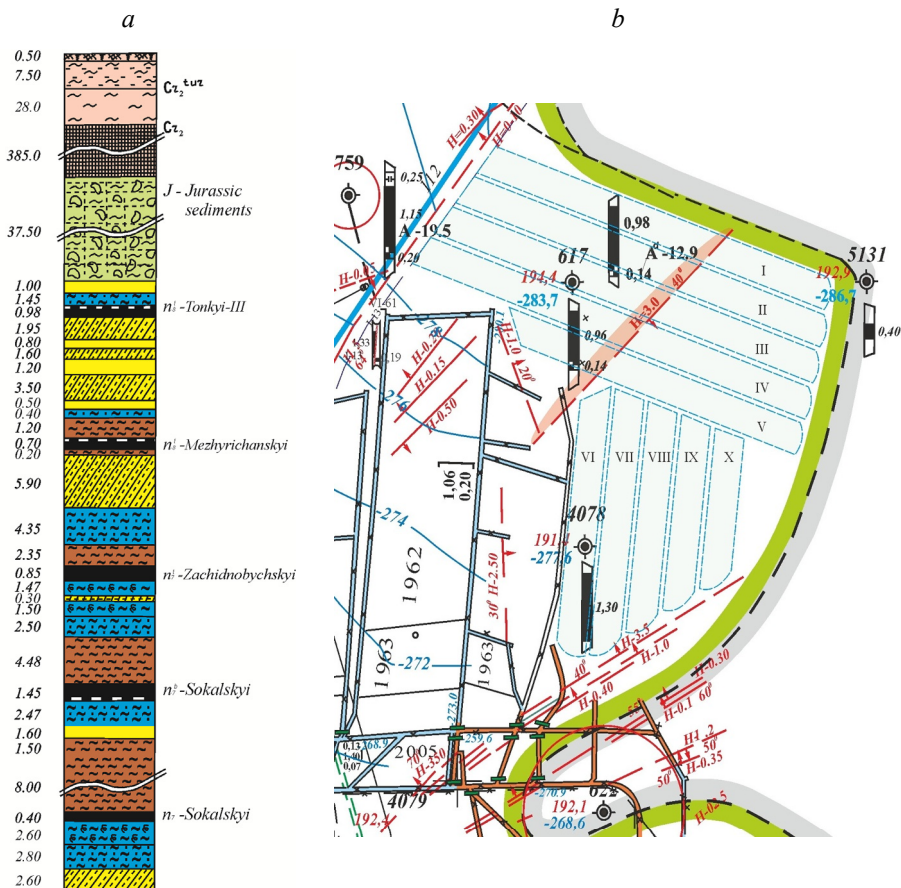

Fig. 2. The stratigraphic column (a) and an area of the mine field of mine "Velykomostivska" through the "Sokalskyi" $n_7{}^b$ seam (b).

The assessment of negative influence of the complex mining and geological conditions when developing various types of minerals are covered in the works of domestic and foreign scientists [37 – 39], therefore, the question of necessity for a more accurate accounting of the geological structure of coal deposits and the properties of host rocks is also of great importance.

Given the long-term experience in uncovering the underground gas generators, the most universal method is the method of uncovering by directionally drilled wells. The configuration of this type of wells should be such that, with minimal expenditures of time

and technological tools, the wells should be brought to the target depth without any complications, as well as to ensure a durable and trouble-free operation. The rational configuration makes it possible to minimize the work with deviation and provide the necessary face displacement.

The curvature radius is the main parameter characterizing the quality of directionally drilled wells. In practice, the well configuration according to the radius is divided into four types: large (> 190 m), mid-radius (60 – 190 m), small (11.5 – 60 m) and short (5.73 – 10 m) curvature radius.

When setting the curvature parameters (zenith angle), the rock composition, the type of drilling equipment, the required wells diameter, etc., are the limiting factors. It is the most appropriate to begin curving the well in stable hard rocks, the trajectory of setting or decreasing the curvature should correspond to the circumference with the corresponding radius. The curvature parameters should be minimum if possible, which will allow to reduce the time of wells driving. But if the well stability in the curvature zone is insufficient, then, if properly substantiated, it may be expedient to increase the curvature parameters.

In the development of thin coal seams by underground gasification, three main geomechanical tasks of well stability can be formulated:

– study of the stress state of the massif, enclosing the vertical blast injection hole and gas drawoff well;

– study of the stress state of the massif in the area of curving and transitioning into a horizontal well;

– study of the stress state of the massif, enclosing the horizontal well that crosses a geological disturbance.

The solution of the problem on studying the stress state of the massif enclosing a horizontal well, which crosses a geological disturbance, as well as the development of technical solutions for the preparation of a gas generator were described earlier in the scientific works of the authors [40, 41].

According to the simulation results, the dependence is determined of change in ultimate stress limits in the rocks around the wells depending on the angle of its entry into the coal seam at certain parameters of the curvature radius. The results will make possible to optimally lay the wells in the massif for reliable operation of the underground gas generator during the period of existence and to predict the possibility of cutting the wells.

To study the geomechanical problems when developing the mineral deposits, various methods of simulation are widely used [42 – 44]. The finite element method makes possible, with an adequate problem formulation and with setting initial data, to reflect the stress state formation of the massif [46, 47], similarly to natural conditions [48, 49]. Therefore, this article is supposed to investigate the stability of producing wells in the coal and rock massif with the use of the computer simulation based on the finite element method [50, 51].

The calculation of the stress state is performed in the software package SolidWorks 2016, which is based on the finite element method. The geomechanical problem was solved in the elastic approach, the obtained stress values were compared with the maximum admissible mine rock values. Due to the fact that the wellbore is mainly exposed to the horizontal component of the rock pressure, as a result of which tensile stresses occur on its contour, the attention was focused on the horizontal stresses distribution when analysing the stresses curves.

After the construction of a geomechanical 3-D model, a triangulation network of finite elements is created, and the finer the network, the more accurate the computational experiment and the longer the time of computation. After the network is created according to the computational scheme developed further, a load should be applied on the geomechanical model of the massif which is fixed from all the sides. Then the stress state calculation is performed with further analysis of the stresses curves. The consideration of the geological structure of mineral deposits and the host rocks properties will make it

possible to obtain the following.

The input data for the simulation:

– the lithological rocks composition (averaged lithological thicknesses in accordance with the mining and geological prediction of the seam n_7^b), according to Fig. 2.

– the physical and mechanical rock properties in accordance with the mining and geological prediction (represented in Table 1);

– the average depth of the seam area development – 450 m;

– the value of load applied to the model – 8 MPa (at an average density of alluviation and massif 1.8 t/m^3);

– the producing well diameter – 250 mm;

– the curvature radius of well in the range of 5 – 25 m, simulated every 5 m for each computational experiment.

Table 1. Physical and mechanical properties of coal and rock massif.

Designation	Sandstone	Siltstone	Coal	Argillite	Limestone
Modulus of elasticity E, MPa	17800	11400	2900	7100	4000
Poisson's ratio, μ	0.25	0.25	0.21	0.23	0.17
Density γ, kg/m^3	2640	2660	1690	2580	2200
Compressive strength, σ_c, MPa	71.1	54.0	23.1	34.0	24
Tensile strength, σ_p, MPa	3.1	3.4	1.4	1.7	1.8

An illustrative view of the curvature radius is represented in the computational scheme (Fig. 3). The horizontal well part, according to gasification technology, was laid in such a way that it was at the distance of 20% from the seam bottom. From the above scheme, it becomes possible to determine the angles of the well entry into the coal seam and increasing the length of the well at various curvature radius, which is an important aspect during its conduction. Analysis of the data, shown in Fig. 3a, makes possible to set an important technological parameter – the angle of well entry into the coal seam, its relationship with the curvature radius is represented in Fig 3b.
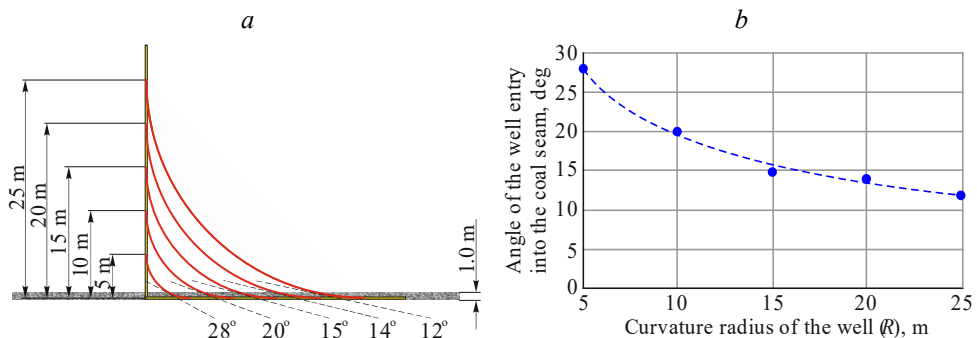

Fig. 3. Determining the parameters of the well curvature radius: (a) computational scheme; (b) the relationship of the well curvature radius with the angle of its entry into the coal seam.

Based on the initial data, a computational scheme has been developed for simulation of the stress state of the "rock massif – producing well" system under the conditions of the mine Velykomostivska for mining the n_7^b seam with presentation of boundary conditions. The finite element model has been created, shown in Fig 4.
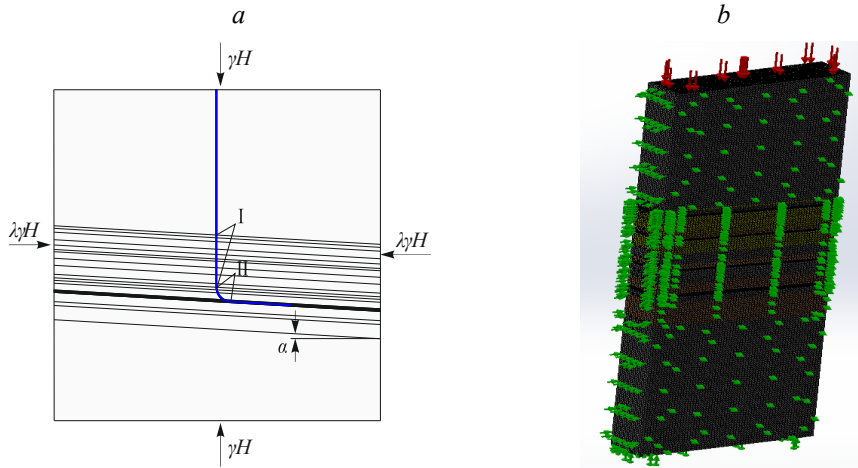
Fig. 4. The computational scheme for simulating SSS of the massif enclosing the well (a) and the constructed finite element model (b).

If according to analysis results of the obtained stresses curves along the upper and lower bounds of the model, the components σ_y corresponding to the stress (γH) of the virgin massif are distributed uniformly, and from the contour of the producing well, the stresses σ_y decrease at a distance much smaller than the lateral boundaries of the model, therefore, the geometrical dimensions of the geomechanical model have been accepted correctly.

Using the sounding function by means of Simulation SolidWorks 2016, it is possible to measure the stresses at any point of the model. Thus, apart from the stresses scale, it is possible to analyse elements which are difficult to access, but often are significantly stressful. On completion of the stress state calculation of the massif enclosing the well, an analysis is performed of the vertical, horizontal stresses components and a prediction is made of the well areas stability in the laminal rock massif.

4 Research results

4.1 Vertical stresses curves analysis

The curves have been obtained of the vertical stresses in the rock massif with a curvature radius of the producing well of 5, 10, 15, 20, 25 m, which are presented in Fig. 5. Analysis of the curves indicates that the stresses field within the lateral model boundaries does not exceed by the value of 7 – 8 MPa and corresponds to the hydrostatic pressure of the virgin massif which is equal to 8 MPa. This evidences that the accepted geomechanical model dimensions are sufficient and the edge effect does not influence on the computational calculation results.

The analysis of curves in Fig. 5 makes possible to state that the stresses field in the coal and rock massif, formed by the vertical stresses component *SY*, is very uniform. There are no significant increases in the stress values to critical values, and all stresses are compressive. The interrupted zones are formed with insignificant compressive stresses in the range of 8.0 – 8.5 MPa between the rock layers. Around the vertical well part, the weak compressive stresses are formed in the range of 6.5 – 7. 5 MPa, which are almost equal to the stress values in the massif undisturbed by mine working (well). In the areas of curving the well when it enters the coal seam, a decrease in the value of compressive stresses is observed, which ranges within the interval of 2.5 – 5.0 MPa.
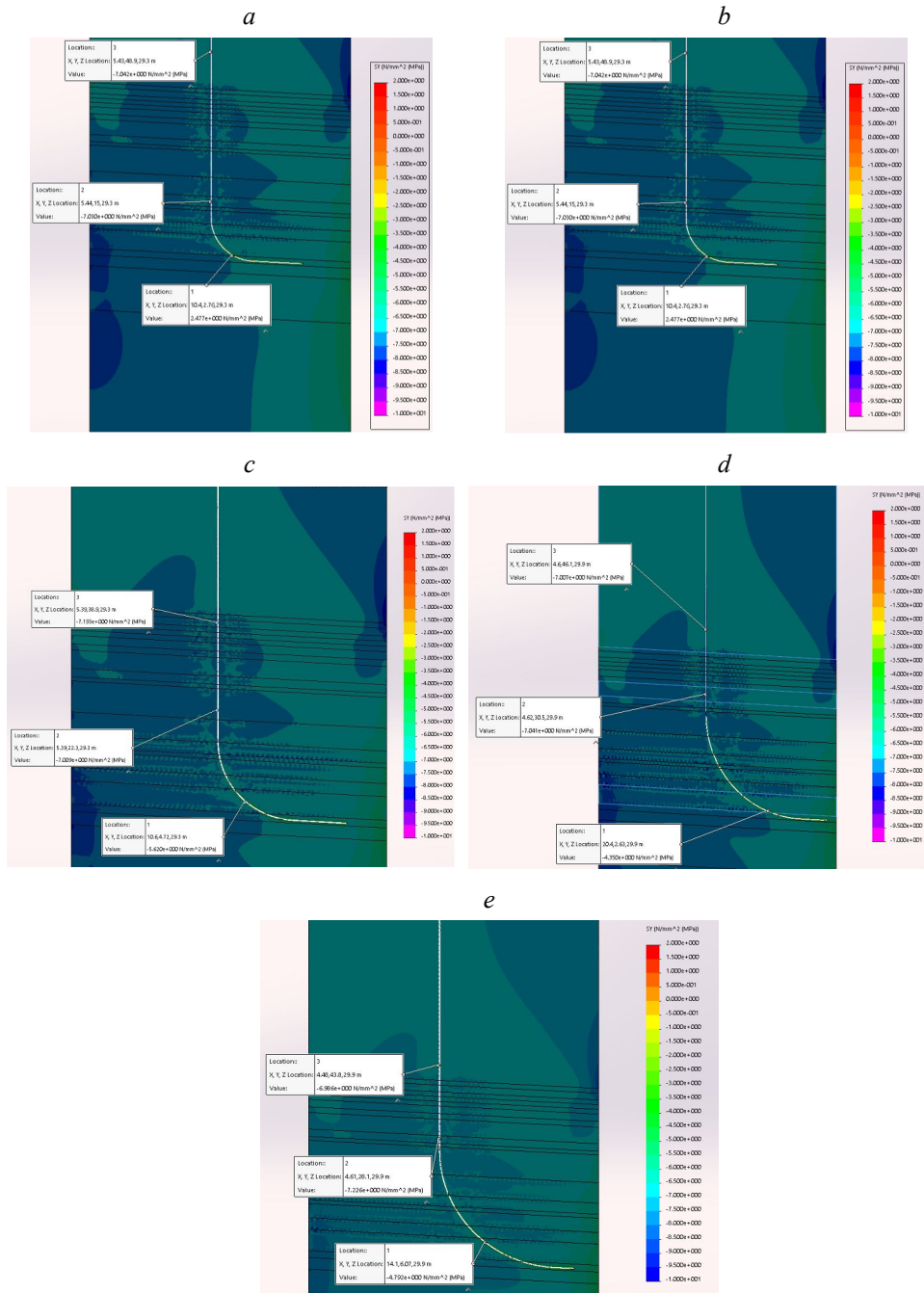
a	*b*

c	*d*

e

Fig. 5. The curves of vertical stresses *SY* in the laminal rock massif with a curvature radius of the producing well: a – 5 m; b – 10 m; c – 15 m; d – 20 m; e – 25 m.

Having compared the identified values of the vertical stresses field with ultimate strength of sandstones, argillites, siltstones and coal, it is evidenced that they do not exceed their compression limit, are not critical and will not lead to destruction when conducting and operating the vertical and curved parts of the wells.

4.2 Horizontal stresses curves analysis

The curves have been obtained of the horizontal stresses in the rock massif with a curvature radius of the producing well of 5, 10, 15, 20, 25 m, which are presented in Fig. 6.
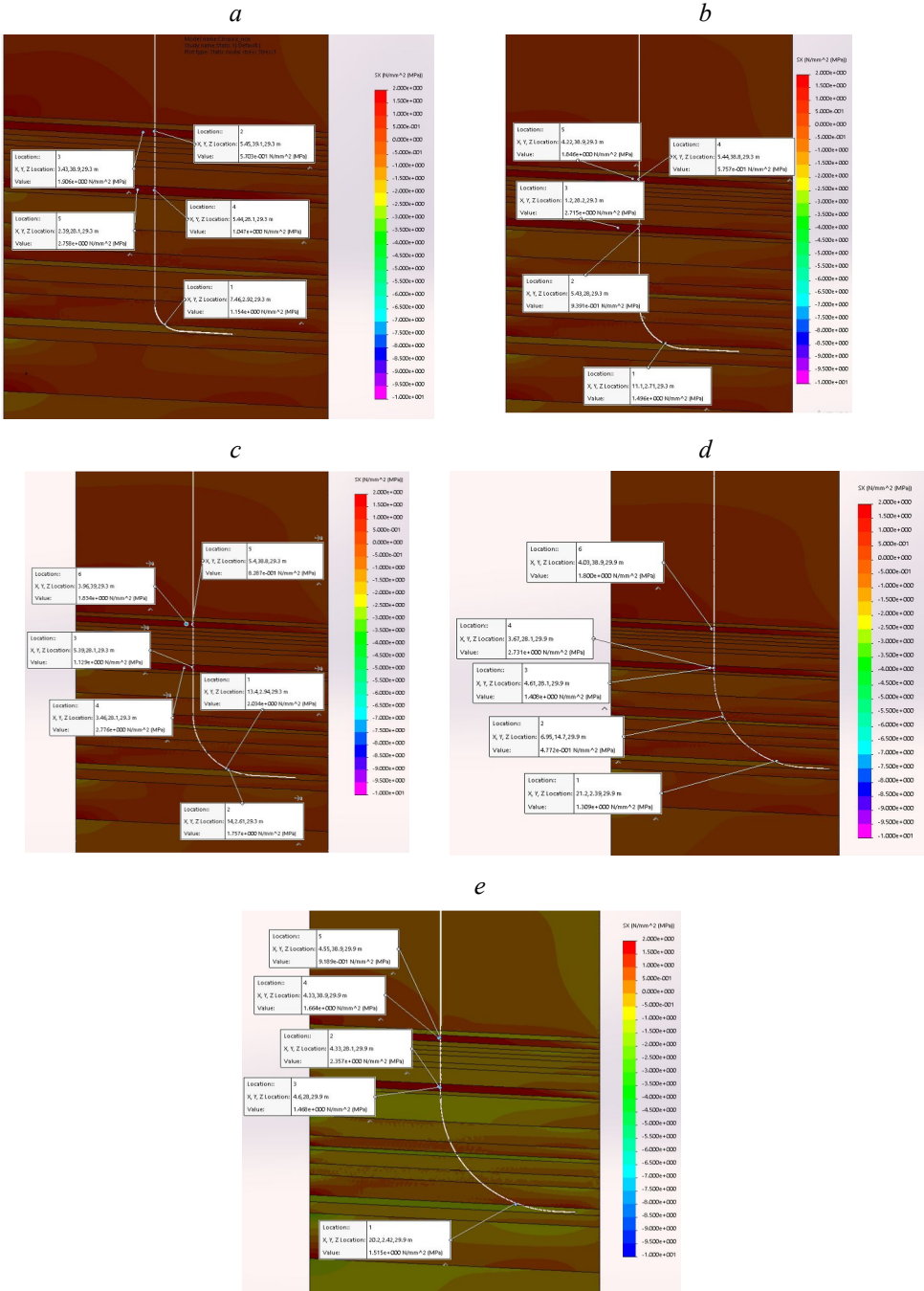

Fig. 6. The curves of horizontal stresses *SX* in the laminal rock massif with a curvature radius of the producing well: a – 5 m; b – 10 m; c – 15 m; d – 20 m; e – 25 m.

The analysis of curves in Fig. 6 indicates that, in a laminal massif the horizontal stresses component *SX* forms various stresses in lithological varieties, including tensile critical stresses, capable of creating the danger of wellbore cutting. This evidences that the prediction of well stability during underground coal gasification must be performed separately for specific mining and geological conditions of bedding the seams, and to create a stresses field, favorable for operating the gasification system by varying the technological parameters (in this case, the curvature radius). The zones of high tensile stresses are formed in the vertical part of the well when crossing the rock layers of argillite and siltstone with a thickness of 1.45 – 1.6 m and reach 1.2 – 2.0 MPa. These stress values are dangerous and contribute to the well cutting effect. The stress values that exceed the ultimate tensile strength of siltstone in the seam roof are critical values in the area of curving the well.

The most dangerous well area has been revealed in the area of curving, where there is a danger of pressing-out the rock layers into the well cavity, which is followed by its cutting. Thus, increased tensile stresses are concentrated in the roof of the seam, in the siltstone layer, where the producing well enters the coal seam at a certain angle.

According to SOU 10.1.00185790.011:2007 "Preparatory mine workings on flat-lying seams. The choice of fasteners, methods and means of protection", the ultimate compressive strength in real conditions is much lower and depends on a complex of influencing factors. The rocks in the area of the studied mine field are laminal (the average distance between the surfaces of weakening is 1.5 – 1.0 m) water-flooded, from light to medium collapse, then the adjusted ultimate compressive strength will be:

$$R = \sigma_c \cdot k_c \cdot k_w \cdot k_t \text{ , MPa,} \tag{1}$$

where σ_c is the ultimate compressive strength of the rock in a sample, MPa; (for siltstone 54 MPa); k_c is the coefficient, taking into account the disturbance of rocks by surfaces of weakening, (0.8); k_w is the coefficient, taking into account the weakening of water-flooded rocks, (0.7); k_t is the coefficient, taking into account the weakening of the rocks under continuous loading, (0.81).

The calculation indicates that the adjusted ultimate compressive strength of siltstone will be 24.5 MPa. For the geological conditions of the seam, the ultimate tensile strength is $0.06\sigma_c$, and the value of tensile strength will be 1.47 MPa. Based on the simulation results, a new dependence has been set of the change in the tensile stress value in the roof rocks of the seam on the angle of the well entry into the coal seam, which is represented in Fig. 7.
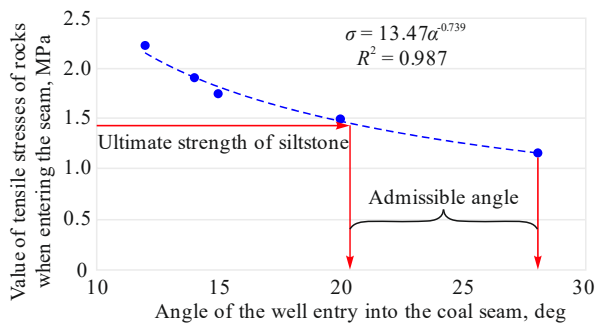

Fig. 7. The dependence of the change in the tensile stress value in the roof rocks on the angle of the well entry into the coal seam.

The analysis of the graph in Fig. 7 shows that the value of tensile stresses in the roof of the seam is exponentially dependent on the angle of the well entry into the seam and is described by the following equation $\sigma = 13.47\alpha^{-0.739}$ with a high level of approximation $R^2 = 0.98$.

Given the ultimate tensile strength of siltstone destruction, it has been set that the rational angle of the well entry into a coal seam is a range of $21 - 28$ degrees, and an appropriate curvature radius will be $5 - 10$ m. The interval of increasing the well length has been estimated depending on an increase in the curvature radius, which is shown in the graph (Fig. 8).
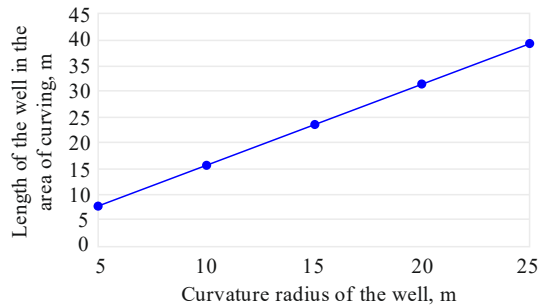

Fig. 8. The influence of the value of the curvature radius on the increasing the well length.

According to Fig. 8, with an appropriate radius of $5 - 10$ m, an increase in the length of the well will be $7.5 - 16$ m. In the future, in the process of drilling the wells, depending on the peculiarities of drilling process, the availability of special equipment and the time of the well conduction, the final curvature radius of the well is adjusted in order to prepare the underground gas generator for operation. That areas of vertical wells, which are under effect of tensile stresses in siltstone and argillite should be strengthened by injecting the grout mix behind the well casing pipes. Thus, under the mining and geological conditions of mine "Velykomostivska" SC "Lvivvuhillia", when developing the n_7^b seam area which is studied from the point of view of underground gasification, the rational curvature radius ensuring the minimum probability is $5 - 10$ m.

5 Conclusions

The design planning of efficient operation of underground gas generators in downhole gasification technology is impossible without consideration of the stress state of the rock massif, enclosing the main uncovering mine workings – blast injection holes and gas drawoff wells. Otherwise, this can lead to a danger of the wellbore cutting and emergency shutdown of the technological system operation. Analysing the information sources, it can be argued that in the study of the underground gas generator operation, these issues are not paid enough attention, especially in the area of well curving when entering the coal seam, which is a stress concentrator with a change in the spatial directionality of the well.

The parameters of geomechanical models have been developed and substantiated for the study of the stress state of the "rock massif – producing well" system, close to real conditions, with account of the physical – mechanical characteristics of the coal and rock laminal stratum, enclosing a coal seam n_7^b in an area of the mine field of the Lviv-Volyn coal basin.

It has been revealed, that under the mining and geological conditions of the n_7^b seam at mine "Velykomostivska" SC "Lvivvuhillia", the value of tensile stresses in the roof of the seam (siltstone) is exponentially dependant on the angle of the well entry into the coal seam and is described by the following equation $\sigma = 13.47\alpha^{-0.739}$ with a high level of approximation $R^2 = 0.98$. Considering the ultimate tensile strength for the siltstone destruction, it has been set that the rational angle of the well entry into a coal seam is a range of $21 - 28$ degrees, and an appropriate curvature radius will be $5 - 10$ m.

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