

Numerical assessment and substantiation of rational geometry for postless hinged support of development mine workings

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Abstract

Purpose. To determine a rational range of inclination angles for the elements of postless hinged support used in development underground mine workings based on a quantitative assessment of their influence on the stress-strain state of the structure.

Methods. Comparative finite-element modelling was performed in ANSYS for a straight horizontal top member ($\alpha = 0^\circ$) and two-element hinged configurations with inclination angles $\alpha = 20, 25, 30$, and 35° . The calculations were carried out under static linear-elastic conditions using identical mechanical properties of the material and a control vertical load of 20 kN. For each configuration, the distributions of displacement and stress intensity were analysed. Comparative assessment was performed using maximum stress intensity, maximum displacement, and normalized and relative indicators of their variation.

Findings. For the straight configuration, the maximum stress intensity was 417.23 MPa, with a maximum displacement of 115.8 mm. The transition to hinged geometry substantially reduced the maximum stress intensity to 184.17 MPa at 20° , 176.77 MPa at 25° , 192.91 MPa at 30° , and 236.10 MPa at 35° . The minimum value was obtained at $\alpha = 25^\circ$, corresponding to a reduction of 57.6% relative to the straight configuration. At the same time, among the hinged configurations, the maximum displacement increased progressively from 168.6 mm at 20° to 293.2 mm at 35° . Thus, the minimum stress and displacement values are achieved at different inclination angles.

Originality. A non-monotonic dependence of maximum stress intensity on the inclination angle of the hinged top-member elements was established, while displacement increased with increasing angle. It was shown that the most favourable geometry according to the stress criterion does not coincide with that according to the deformation criterion, which substantiates the joint use of both indicators when selecting the geometric parameters of the support.

Practical implications. For the adopted loading conditions and numerical formulation, the range $\alpha = 20\text{--}25^\circ$ was identified as rational: at 20° , the minimum displacement among the investigated hinged configurations is achieved, whereas at 25° , the minimum maximum stress intensity is obtained. The results can be used as a preliminary basis for selecting support geometry prior to comprehensive modelling of the interaction within the “rock mass-support” system and subsequent experimental or field validation.

Keywords: mine working; support; hinged support; finite element method; stress-strain state; numerical modelling

1. Introduction

Ensuring the stability of development mine workings is one of the key challenges in underground mineral extraction. As mining depth increases and mining and geological conditions become more complex, the requirements for the bearing capacity, stiffness, and deformation capacity of support structures become more stringent [1], [2]. At the same time, support performance is determined not only by the mechanical properties of the material but also by the geometry of the load-bearing system, support conditions, the type of connections between individual elements, and the mechanism of external load transfer to the bearing sections and the surrounding rock mass [3].

Modern numerical modelling methods are widely used to analyse the stress-strain state of geomechanical systems and to substantiate rational structural parameters [4], [5]. Mathematical modelling is also applied to analyse dynamic loads and substantiate the operating modes of mining systems and equipment [6]. The finite element method is widely used to analyse the interaction within the “rock mass-support” system, assess displacements of the excavation contour, determine loads acting on support elements, and investigate their bearing capacity [7]–[11]. This approach makes it possible to quantitatively compare different structural solutions under specified material properties, boundary conditions, and external loading.

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One of the factors that significantly affects the mechanical behaviour of support structures is the geometric shape of their load-bearing elements. Studies of frame, U-shaped, and combined steel supports show that changes in structural configuration affect the distribution of internal forces, the magnitude of bending moments, the location of stress concentration zones, and the overall deformability of the system [12]–[16]. At the same time, the performance of load-bearing structures is determined not only by their geometry but also by the physical, mechanical, and operational properties of the materials used. Increasing the strength of metallic elements, particularly bar components, is considered one of the approaches to reducing metal consumption while maintaining the required load-bearing characteristics [17]. In addition to strength characteristics, the damping and vibration properties of metallic materials may also be important under dynamic loading and can be purposefully modified through the selection of alloy composition, heat treatment, and the application of nanostructured coatings [18]–[20].

For steel elements, maintaining the service properties of the material throughout its service life is also of considerable importance. Studies of carbon and low-carbon steels highlight the relevance of surface modification and corrosion protection methods. In particular, technologies for phosphating carbon steel using technogenic raw materials have been investigated [21], along with the influence of phosphating solution preparation conditions on their composition and properties [22], as well as the use of manganese-containing waste-processing products as corrosion inhibitors for low-carbon steel [23]. These approaches indicate that the service reliability of metallic elements is determined not only by their initial strength but also by the surface condition, interaction with the external environment, and the material resistance to degradation processes.

In a broader materials science context, the mechanical and service properties of structural materials can be purposefully modified through the selection of composition, production technology, and internal structure [24]. The development of composite materials based on mineral and slag components represents one approach to controlling the properties of structural systems [25], while selective processing of slag raw materials can improve the physical and mechanical characteristics of the resulting materials [26]. The relationship between structural state and mechanical properties is also observed in other classes of materials: phase transformations can affect the strength characteristics and heat resistance of ceramic systems [27], whereas the accumulation of structural defects may be accompanied by changes in the material state and degradation of its near-surface layer [28].

Thus, the mechanical response of a load-bearing system is generally governed by the combined influence of geometric, materials-related, and operational factors. In the present study, the influence of material properties was deliberately excluded from the set of varied parameters: identical mechanical properties of steel were used for all numerical configurations. This approach made it possible to isolate the effect of the geometric configuration of the top member and the inclination angle of its elements on the stress-strain state of the structure.

Geometry becomes particularly important for multi-element structures in which individual members are connected by hinges. The mechanical characteristics of the connections and the manner in which a steel support is divided into

individual sections significantly affect its bearing capacity, deformability, and distribution of internal forces [29], [30]. In such a system, the inclination angle of the elements becomes an independent parameter governing the kinematic scheme and the mechanism of load transfer. Compared with a straight horizontal member, the inclined arrangement of the top-member sections may alter the relationship between the bending and axial components of the internal forces and thereby affect the maximum stress level.

At the same time, a reduction in stress is not necessarily accompanied by a decrease in displacement. Changes in geometry may reduce the bending component of the load while simultaneously increasing the overall compliance of the structure. Consequently, a configuration that is most favourable in terms of the strength criterion is not necessarily the most effective from the standpoint of stiffness [31], [32]. Therefore, the assessment of hinged support requires the combined consideration of at least two characteristics: the stress level and the magnitude of displacement.

Despite the considerable number of studies devoted to the analysis of frame, arched, and U-shaped supports and the interaction of support structures with the surrounding rock mass [33], the quantitative influence of the inclination angle of two hinged top-member elements on the combination of strength and deformation characteristics requires further investigation. Of particular interest is the identification of an angle range within which a substantial reduction in maximum stresses is not accompanied by an excessive increase in structural displacements.

The present study considers a postless top-member structure consisting of two hinged elements. A straight horizontal top member is used as the baseline configuration, and its stress-strain state is compared with that of hinged configurations with element inclination angles of 20, 25, 30, and 35°. The comparison is performed using identical mechanical properties of the material, the same principles for specifying boundary conditions, and the same magnitude of the control vertical load.

The aim of the study is to establish the patterns of change in the stress-strain state of postless hinged support with variation in the inclination angle of the top-member elements and to substantiate a rational range of geometric parameters based on a combined analysis of maximum stresses and displacements.

2. Materials and methods

2.1. Numerical study design

The numerical study was performed using the ANSYS software package and was designed as a comparative parametric analysis of the stress-strain state of different geometric configurations of the top member of a postless support. The primary objective of the modelling was to isolate the effect of the inclination angle of the top-member elements on the mechanical response of the structure while maintaining constant material properties and identical external loading.

The study included five numerical configurations: a baseline straight configuration with $\alpha = 0^\circ$ and four two-element hinged configurations with inclination angles $\alpha = 20^\circ, 25^\circ, 30^\circ$, and 35° . For each configuration, a finite-element model was developed, identical mechanical properties of the material were assigned, and a control vertical load of 20 kN was applied. The inclination angle α was the only geometric para-

meter varied. The analysis was performed under static linear-elastic conditions. The load of 20 kN was adopted as a control value for comparative analysis and was not intended to reproduce a specific level of rock pressure in an actual mine working. Maintaining the same load and mechanical properties of the material for all configurations made it possible to relate changes in the calculated structural response primarily to changes in geometric configuration.

The maximum stress intensity and maximum structural displacement were used as the main output parameters. These indicators characterize changes in the stress state and overall deformability of the investigated configurations,

respectively. In addition, normalized dimensionless criteria and relative changes in the calculated parameters were used for comparative evaluation of the results; the procedure for their determination is presented below.

The computational experiment included the definition of the geometric configuration and boundary conditions, assignment of the mechanical properties of the material, finite-element analysis, determination of the maximum stress and displacement values, and subsequent comparison of the obtained results. The main stages of the parametric analysis are presented in Table 1.

Table 1. Sequence of the parametric finite-element analysis and calculated parameters

Stage	Input data	Computational operation	Output parameter
1	$\alpha = 0^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ; P = 20 \text{ kN}$	Definition of geometry and boundary conditions	Comparable configurations
2	$E = 200 \text{ GPa}; \nu = 0.30$	Linear-elastic finite-element solution	Nodal displacement vector u
3	Displacement field	Determination of maximum displacement	$u_{\max}$, mm
4	Stress field	Determination of maximum stress intensity	$\sigma_{\max}$, MPa
5	$\sigma_{\max}$ and $u_{\max}$ for all α	Normalization and relative comparison	$K_\sigma, K_u, \Delta\sigma, \Delta u$

2.2. Finite-element formulation

The stress-strain state of the investigated structures was calculated using the finite element method under static linear-elastic conditions. For each value of the element inclination angle α , the equilibrium of the discretized structure was described by the system of finite-element equations:

$$K(\alpha)u = F, \quad (1)$$

where:

$K(\alpha)$ – global stiffness matrix of the structure, dependent on the geometry of the numerical scheme and the element inclination angle α ;

u – nodal displacement vector;

F – external nodal load vector.

With unchanged mechanical properties of the material and the same magnitude of external loading, a change in the geometric configuration of the top member results in a change in the stiffness matrix $K(\alpha)$, which, in turn, determines the variation in the calculated nodal displacement field.

The relationship between nodal displacements and strains in the structural elements was determined as:

$$\varepsilon = Bu, \quad (2)$$

where:

ε – strain vector;

B – strain-displacement matrix.

Within the linear-elastic model, the relationship between strains and stresses was described by:

$$\sigma = D\varepsilon, \quad (3)$$

where:

σ – stress vector;

D – elastic constitutive matrix of the material, determined by Young's modulus E and Poisson's ratio ν .

Thus, under identical material properties and external loading, changes in the geometry of the numerical scheme lead to changes in its stiffness and, consequently, in the distributions of displacements and stresses. The displacement and stress fields obtained from the finite-element analysis were subsequently used to determine the maximum calculated parameters and to perform a comparative analysis of the investigated geometric configurations.

2.3. Material properties and loading conditions

To ensure comparability of the investigated geometric configurations, the same set of mechanical material properties and the same magnitude of external loading were used in all calculations. The adopted parameters are presented in Table 2.

Table 2. Mechanical properties of the material and loading conditions adopted in the numerical model

Parameter	Adopted value	Note
Young's modulus E	$2 \cdot 10^5 \text{ MPa}$ (200 GPa)	Adopted for the steel structure in the numerical model
Poisson's ratio ν	0.30	Linear-elastic material model
Control strength characteristic	400 MPa	Used for comparative assessment of the calculated stresses
Vertical load P	20 kN	Identical for all numerical configurations

For the steel elements, Young's modulus was taken as $E = 2 \cdot 10^5 \text{ MPa}$ (200 GPa), and Poisson's ratio as $\nu = 0.30$. The material in the numerical model was treated as linear-elastic, in accordance with the adopted problem formulation.

The value of 400 MPa was used as a control strength characteristic for comparative assessment of the calculated stresses. In the present study, this value is not associated with any specific steel grade and is used as a reference level for interpretation of the results. The vertical load $P = 20 \text{ kN}$ was kept identical for all investigated geometric configurations. Its value was adopted as a control load for the parametric comparison and was not intended to reproduce a specific level of rock pressure in an actual mine working. This approach made it possible to compare the response of different configurations under identical external loading.

For the baseline straight configuration, the maximum calculated stress intensity is 417.23 MPa, which exceeds the adopted control value of 400 MPa. Therefore, this configuration is considered as a comparative baseline case. For practical design applications, verification against the actual mechanical properties of the selected steel grade is required, while an appropriate nonlinear material model should be applied if the material response extends beyond the elastic range.

2.4. Geometry and boundary conditions

To formalize the numerical problem and unambiguously define the varied geometric parameter, a two-element top-member configuration with a central hinge and support at the lateral sections of the mine working was adopted. The schematic numerical model of the postless hinged support, the direction of the vertical load, and the varied inclination angle α are shown in Figure 1.

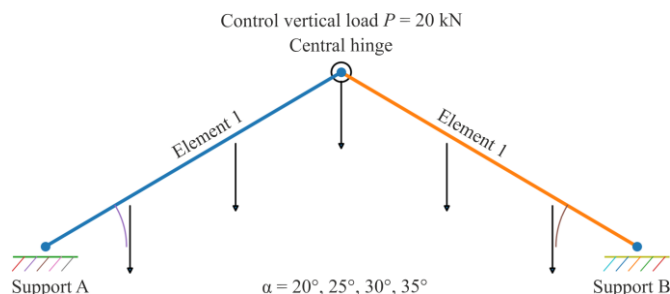


Figure 1. Numerical scheme of the two-element hinged top member: geometric parameter α , central hinge, support conditions, and direction of the control vertical load

A straight horizontal top member with $\alpha = 0^\circ$, supported at both ends, was considered as the baseline configuration. The hinged numerical scheme consisted of two inclined elements connected to each other at the central section and supported by their lower ends at the lateral sections of the mine working. For the parametric analysis, inclination angles $\alpha = 20^\circ, 25^\circ, 30^\circ$, and 35° were investigated. The angle α was measured relative to the horizontal direction.

In all numerical configurations, the vertical load $P = 20$ kN was applied under identical loading conditions. The mechanical properties of the material were also kept unchanged. Thus, the comparison of the numerical configurations was aimed at evaluating changes in the stress-strain

state of the structure caused by changes in its geometric configuration and the inclination angle α of the elements.

The central hinged connection allowed relative rotation of the elements and governed the load-transfer mechanism from the central part of the top member to the support sections. As the angle α changed, the spatial position of the elements also changed, affecting the stiffness of the numerical scheme and the distribution of internal forces. The specific redistribution of stresses and displacements was determined directly from the finite-element modelling results.

It should be noted that the model was used for a comparative parametric analysis of the investigated geometric configurations rather than as a final design model for a specific mine working. Therefore, the obtained absolute values apply to the adopted numerical scheme and boundary conditions. For the design of support under specific mining and geological conditions, the actual dimensions and profiles of the elements, real support conditions, and interaction of the structure with the surrounding rock mass should additionally be taken into account.

2.5. Finite-element discretization and model limitations

To assess the reliability of the comparative finite-element analysis, the discretization characteristics of the numerical models were considered. The available numerical images show that the finite-element mesh was generated along the entire length of the top-member elements and maintained a regular pattern. Particular attention during interpretation of the results was paid to regions where changes in geometry and load-transfer conditions may be accompanied by increased stress gradients, primarily the central hinged connection and the support zones.

The main features of the applied discretization and the monitored regions of the numerical model are presented in Table 3.

Table 3. Characteristics of the finite-element discretization and monitored model regions

Monitored region	Discretization characteristics	Purpose	Interpretation features
Along the element length	Along the element length	Description of the overall deformed shape of the structure	Uniform discretization approach for the compared configurations
Central hinged connection	Locally sensitive region	Load transfer and relative rotation of the elements	Increased stress gradients may occur
Support zones	Locally sensitive region	Transfer of structural reaction to the supports	Local stress concentrations may occur

A consistent discretization approach was applied to all investigated geometric configurations, ensuring comparability of the numerical results within the adopted parametric analysis. The central hinged connection and the support zones were regarded as the most sensitive regions because changes in the direction of load transfer in these areas may lead to local increases in stress gradients.

A quantitative mesh-convergence study was not performed in the present work. The original ANSYS files containing several finite-element mesh variants were not available; therefore, the dependence of the obtained maximum stress and displacement values on the degree of mesh refinement was not assessed. This limitation should be taken into account when interpreting the absolute numerical values.

At the same time, the comparative analysis of the geometric configurations was performed using the same ap-

proach to model construction and discretization. Therefore, the obtained results are considered primarily as a basis for assessing the relative influence of changes in the element inclination angle α on the stress-strain state of the structure, whereas a final design analysis would require an additional sensitivity assessment with respect to the finite-element mesh parameters.

2.6. Evaluation criteria and comparative analysis

Two primary calculated parameters were used for quantitative comparison of the investigated geometric configurations: maximum stress intensity and maximum structural displacement. Since these parameters have different physical dimensions, normalized dimensionless coefficients were additionally introduced to compare changes in the strength and deformation response as the element inclination angle α varied.

The relative stress-level coefficient was defined as:

$$K_{\sigma} = \frac{\sigma_{\alpha}}{\sigma_0}, \quad (4)$$

where:

σ_{α} – maximum stress intensity at a given angle α ;

σ_0 – maximum stress intensity for the baseline straight configuration at $\alpha = 0^{\circ}$.

The value of K_{σ} represents the ratio of the maximum stress in the investigated configuration to that in the baseline straight configuration. To assess changes in the deformability of the hinged configurations, the relative coefficient was used:

$$K_u = \frac{u_{\alpha}}{u_{20}}, \quad (5)$$

where:

u_{α} – maximum displacement at a given angle α ;

u_{20} – maximum displacement of the hinged configuration at $\alpha = 20^{\circ}$.

The configuration with $\alpha = 20^{\circ}$ was adopted as the reference for displacement normalization because this criterion was compared within the group of investigated hinged configurations. The value of K_u was not determined for the straight configuration. In addition, the relative change in maximum stress intensity with respect to the baseline straight configuration was calculated as:

$$\Delta\sigma = \frac{\sigma_{\alpha} - \sigma_0}{\sigma_0} \cdot 100\%. \quad (6)$$

The relative change in the maximum displacement of the hinged configurations with respect to the $\alpha = 20^{\circ}$ configuration was determined as:

$$\Delta u = \frac{u_{\alpha} - u_{20}}{u_{20}} \cdot 100\%. \quad (7)$$

A negative value of $\Delta\sigma$ indicates a reduction in maximum stress intensity relative to the straight configuration, whereas a positive value of Δu indicates an increase in displacement relative to the hinged configuration with $\alpha = 20^{\circ}$.

Thus, the comparative analysis was performed using the absolute values of maximum stress intensity and maximum displacement, as well as the normalized coefficients K_{σ} and K_u and the relative changes $\Delta\sigma$ and Δu . The combined consideration of these parameters was used to assess the trade-off between stress reduction and increased deformability and to subsequently substantiate a rational range of inclination angles for the top-member elements.

3. Results and discussion

3.1. Response of the baseline straight configuration

At the first stage, the baseline straight configuration of the top member at $\alpha = 0^{\circ}$ was analysed and used as the reference case for subsequent comparison with the hinged configurations. To evaluate its stress-strain state, the distribution of vertical displacements and the spatial field of stress intensity were considered. The deformed shape of the straight top member in the 2D representation is shown in Figure 2. The displacement distribution is symmetrical, with the maximum vertical deflection occurring in the central part of the span. The maximum displacement is 115.8 mm. The spatial distribution of stress intensity for the same numerical configuration is presented in Figure 3.

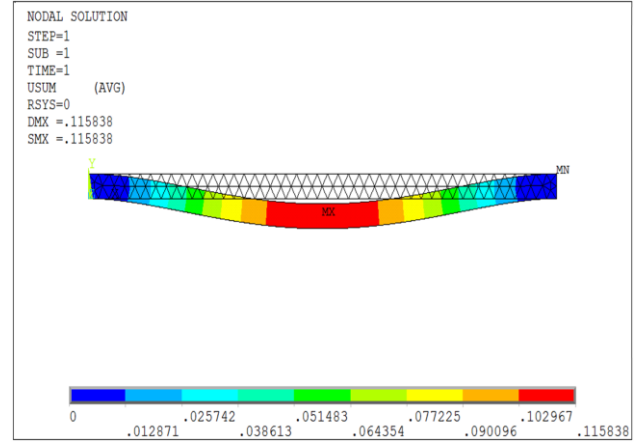


Figure 2. Y-axis displacement in the 2D projection for the straight beam

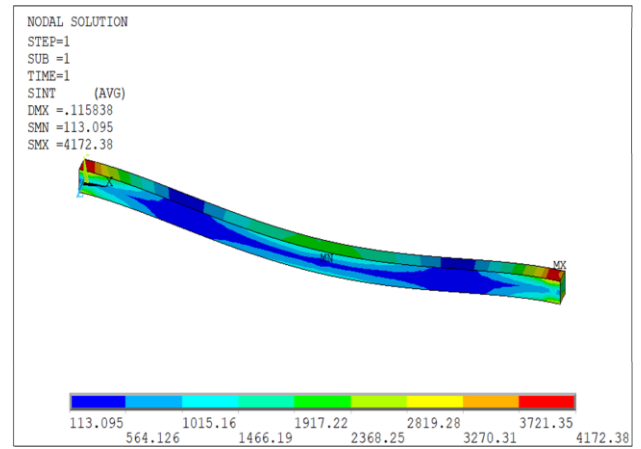


Figure 3. Stress intensity of the straight beam in the 3D projection

The stress field is characterized by a non-uniform distribution along the length of the element. The maximum calculated stress intensity reaches 417.23 MPa, which is the highest value among all investigated geometric configurations. This value also exceeds the control strength characteristic of 400 MPa adopted in the study; therefore, the straight configuration is considered an unfavourable baseline case for subsequent comparative analysis.

Thus, the baseline configuration is characterized by a relatively low displacement level while exhibiting the highest stress level among the investigated configurations. This combination makes it a suitable reference case for quantitatively assessing how the introduction of a central hinged connection and variation in the element inclination angle affect the stress state and deformability of the structure.

3.2. Effect of the inclination angle on the structural response

The transition from the straight configuration to a two-element hinged configuration substantially changes the deformation behaviour and stress state of the top member. To evaluate the effect of the element inclination angle, configurations with $\alpha = 20^{\circ}$, 25° , 30° , and 35° were considered sequentially. For each angle, the distribution of vertical displacements in the 2D representation and the spatial distribution of stress intensity in the 3D representation were analysed. The results for all investigated hinged configurations are combined in Figure 4.

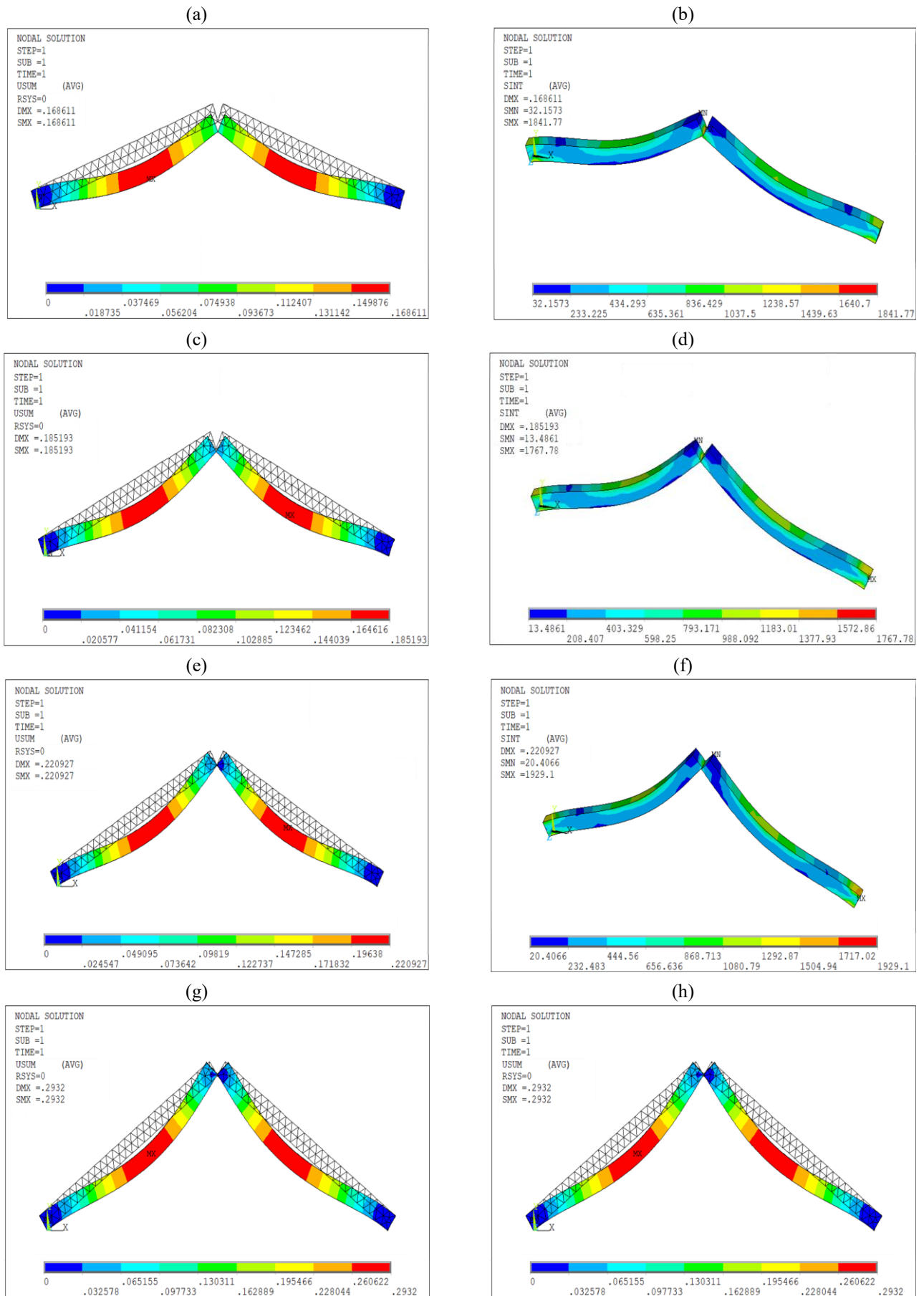


Figure 4. Numerical results for hinged configurations at different inclination angles: (a) displacement along the Y-axis at $\alpha = 20^\circ$; (b) stress intensity at $\alpha = 20^\circ$; (c) displacement along the Y-axis at $\alpha = 25^\circ$; (d) stress intensity at $\alpha = 25^\circ$; (e) displacement along the Y-axis at $\alpha = 30^\circ$; (f) stress intensity at $\alpha = 30^\circ$; (g) displacement along the Y-axis at $\alpha = 35^\circ$; (h) stress intensity at $\alpha = 35^\circ$

At $\alpha = 20^\circ$, the maximum structural displacement is 168.6 mm (Fig. 4a). The deformed shape remains symmetrical with respect to the central hinged connection. Among the investigated hinged configurations, this is the minimum displacement value; therefore, this configuration is characterized by the lowest deformability within the considered group. At the same time, the maximum stress intensity decreases to 184.17 MPa (Fig. 4b), which is 55.9% lower than that of the baseline straight configuration. Thus, even at an angle of 20° , the transition to hinged geometry is accompanied by a substantial reduction in the maximum stress level.

When the angle is increased to $\alpha = 25^\circ$, the maximum displacement increases to 185.1 mm (Fig. 4c), which is 9.8% higher than the value obtained for the 20° configuration. At the same time, the maximum stress intensity decreases to 176.77 MPa (Fig. 4d). This is the minimum value among all investigated configurations and corresponds to a reduction of 57.6% relative to the straight top member. Therefore, the transition from 20° to 25° slightly increases structural deformability while providing a further reduction in the maximum stress level. The obtained result shows that the most favourable inclination angles according to the stress and deformation criteria do not coincide.

At $\alpha = 30^\circ$, the maximum displacement increases to 220.9 mm (Fig. 4e), which is 31.0% higher than that of the hinged 20° configuration. The maximum stress intensity also increases and reaches 192.91 MPa (Fig. 4f). Although this value remains 53.8% lower than that of the straight configuration, it is already higher than the minimum value obtained at $\alpha = 25^\circ$. Thus, after the minimum stress level is reached at 25° , a further increase in the angle is accompanied by simultaneous increases in both stress and displacement.

For the $\alpha = 35^\circ$ configuration, a further increase in structural deformability is observed. The maximum displacement reaches 293.2 mm (Fig. 4g), which is the highest value among all investigated numerical configurations and is 73.9% higher than that of the hinged 20° configuration. At the same time, the maximum stress intensity increases to 236.10 MPa (Fig. 4h). Although this value remains lower than that of the straight configuration, it exceeds the minimum value obtained at $\alpha = 25^\circ$ by 33.6%. Therefore, increasing the angle to 35° does not provide any additional reduction in stress and is simultaneously accompanied by a substantial increase in displacement.

Overall, the results demonstrate different trends in the two analysed parameters. Within the investigated range of hinged configurations, the maximum displacement increases consistently with increasing inclination angle, from 168.6 mm at 20° to 293.2 mm at 35° . In contrast, the maximum stress intensity varies non-monotonically: it decreases from 184.17 MPa at 20° to a minimum value of 176.77 MPa at 25° , after which it increases to 192.91 and 236.10 MPa at 30° and 35° , respectively. Consequently, increasing the inclination angle beyond 25° does not lead to any further improvement in the stress state and is simultaneously accompanied by increased structural deformability. This trend highlights the trade-off between reducing stress intensity and maintaining sufficient structural stiffness. This provides the basis for the subsequent comparative analysis of the strength and deformation criteria and for substantiating a rational range of inclination angles for the top-member elements.

3.3. Comparative analysis of stresses and displacements

To summarize the finite-element modelling results, the maximum stress intensity and maximum displacement were compared for all investigated geometric configurations. The calculated values and their relative changes are presented in Table 4.

Table 4. Comparison of calculated stresses and displacements for the investigated geometric configurations

Parameter	Angle, °				
	0	20	25	30	35
Maximum stress intensity, MPa	417.23	184.17	176.77	192.91	236.1
Maximum displacement, mm	115.8	168.6	185.1	220.9	293.2
Change in stress relative to 0° , %	0	-55.9	-57.6	-53.8	-43.4
Change in displacement relative to 20° , %	–	0	9.8	31	73.9

Comparison of the results shows that the transition from the straight configuration to hinged configurations leads to a substantial reduction in maximum stress intensity. For the baseline configuration at $\alpha = 0^\circ$, the maximum value is 417.23 MPa, whereas at $\alpha = 20^\circ$ and 25° it decreases to 184.17 and 176.77 MPa, respectively. The minimum value is reached at $\alpha = 25^\circ$, corresponding to a reduction of 57.6% relative to the baseline straight configuration.

With a further increase in the inclination angle, the opposite trend is observed. At $\alpha = 30^\circ$, the maximum stress intensity increases to 192.91 MPa, while at $\alpha = 35^\circ$ it reaches 236.10 MPa. Thus, the dependence of maximum stress intensity on the inclination angle is non-monotonic: after a sharp decrease following the transition to the hinged configuration, the minimum is reached at 25° , after which the stress level increases again.

The variation in maximum displacement follows a different trend. For the straight configuration, the maximum displacement is 115.8 mm, whereas for the hinged configurations it increases from 168.6 mm at 20° to 293.2 mm at 35° . Within the group of hinged configurations, the minimum displacement corresponds to an angle of 20° . When the angle is increased to 25° , 30° , and 35° , the displacement increases relative to this configuration by 9.8, 31.0, and 73.9%, respectively.

Therefore, changes in geometry affect the two considered parameters differently. The transition to a hinged configuration substantially reduces the maximum stress level but is accompanied by increased displacement compared with the baseline straight configuration. Within the group of hinged configurations, the minimum stress intensity is achieved at $\alpha = 25^\circ$, whereas the minimum displacement corresponds to $\alpha = 20^\circ$. At angles of 30° and 35° , both stress and displacement increase compared with the 25° configuration.

The obtained results show that the selection of a rational geometry cannot be based on a single calculated parameter. Both the stress state and structural deformability should be considered jointly. To eliminate the influence of the different dimensions of these criteria, they are further normalized and compared in dimensionless form. This increase reflects a progressive rise in structural compliance as the inclination angle becomes larger.

3.4. Normalized assessment and rational inclination range

For the joint assessment of the strength and deformation criteria, the absolute values of maximum stress intensity and maximum displacement were additionally presented in normalized form. This approach makes it possible to compare parameters with different physical dimensions and quantitatively assess changes in the mechanical response of the structure as the inclination angle of the top-member elements varies. Normalization was performed according to the K_σ and K_u criteria defined in Section 2.6.

Table 5. Normalized parameters of the stress-strain state of the support at different inclination angles of the top-member elements

Parameter	Inclination angle α , °				
	0	20	25	30	35
Maximum stress intensity, MPa	417.23	184.17	176.77	192.91	236.10
Maximum displacement, mm	115.80	168.60	185.10	220.90	293.20
$K_\sigma = \sigma_\alpha / \sigma_0$	1000	0.441	0.424	0.462	0.566
$K_u = u_\alpha / u_{20}$	–	1000	1098	1310	1739
$\Delta\sigma$ relative to 0°, %	0.0	-55.9	-57.6	-53.8	-43.4
Δu relative to 20°, %	–	0.0	9.8	31.0	73.9

The normalized stress coefficient K_σ confirms a pronounced reduction in maximum stress intensity when transitioning from the straight to the hinged configuration. At $\alpha = 20^\circ$, K_σ is 0.441, meaning that the maximum stress intensity decreases to 44.1% of the level obtained for the baseline straight configuration. When the angle is increased to $\alpha = 25^\circ$, the coefficient decreases to its minimum value of 0.424, corresponding to 42.4% of the baseline level.

At the same time, the displacement coefficient K_u shows the opposite trend. For the hinged configuration at $\alpha = 20^\circ$, adopted as the reference for this criterion, $K_u = 1.000$. At $\alpha = 25^\circ$, the coefficient increases to 1.098, meaning that the maximum displacement increases by 9.8%. Thus, the additional reduction in maximum stress intensity when moving from 20° to 25° is approximately 4%, whereas the displacement increases by almost 10%. This quantitatively confirms the trade-off between reducing the stress level and maintaining structural stiffness.

With a further increase in the angle to 30° and 35° , both normalized parameters change in an unfavourable direction. The value of K_σ increases to 0.462 and 0.566, respectively, while K_u increases to 1.310 and 1.739. Therefore, after the minimum stress level is reached at $\alpha = 25^\circ$, a further increase in the angle no longer provides any additional reduction in maximum stress intensity and is simultaneously accompanied by a substantial increase in displacement.

For a clear representation of the identified trends, the absolute and normalized calculated parameters are presented in Figure 5. The dependence of maximum stress intensity on the inclination angle is distinctly non-monotonic (Fig. 5a). After a sharp decrease following the transition from the straight to the hinged configuration, the minimum value is reached at $\alpha = 25^\circ$, after which the stress intensity increases again at 30° and 35° . In contrast, the maximum displacement within the range of hinged configurations increases progressively with increasing inclination angle (Fig. 5b), indicating an increase in structural compliance.

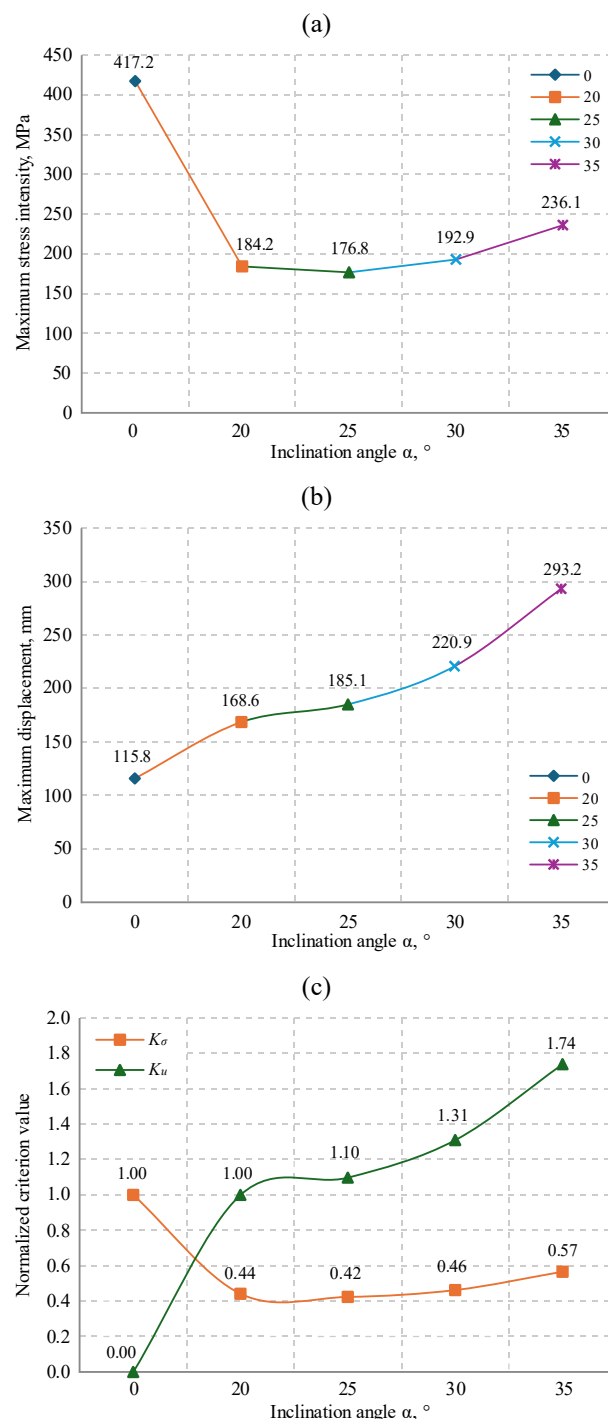


Figure 5. Effect of the inclination angle of the top-member elements on the calculated characteristics of the hinged support: (a) maximum stress intensity; (b) maximum displacement; (c) normalized criteria K_σ and K_u

The combined representation of the normalized criteria K_σ and K_u (Fig. 5c) shows that the most favourable values of the two considered parameters do not coincide. The 20° configuration is characterized by the minimum displacement among the hinged configurations, whereas the minimum maximum stress intensity is achieved at 25° . At angles greater than 25° , both stress intensity and displacement increase simultaneously; therefore, a further increase in inclination provides no additional benefit within the adopted numerical setup.

Thus, considering the two criteria jointly, the range $\alpha = 20\text{--}25^\circ$ can be identified as rational for the investigated numerical scheme. The lower boundary of this range corresponds to lower deformability of the hinged structure, whereas the upper boundary provides the minimum level of maximum stress intensity. The selection of a specific value within this range should be determined by the allowable displacement level and the actual strength requirements imposed on the support.

3.5. Discussion of the obtained trends and study limitations

The obtained results show that changes in the geometry of the top member have a substantial effect on the stress-strain state of the postless hinged support. The transition from the straight configuration to the two-element hinged configuration leads to a significant reduction in maximum stress intensity throughout the investigated angle range of $20\text{--}35^\circ$. At the same time, an increase in the inclination angle is accompanied by increasing displacement, indicating greater structural compliance. A similar sensitivity of the deformation response to the structural configuration and operating conditions of the support system has also been reported in recent studies of deep mine workings [34], [35]. Thus, a reduction in stress is not accompanied by a simultaneous decrease in deformation, and the most favourable inclination angles according to the two considered criteria do not coincide.

The minimum maximum stress intensity was obtained at $\alpha = 25^\circ$, whereas the minimum displacement among the hinged configurations corresponds to $\alpha = 20^\circ$. When the angle increases beyond 25° , both stress intensity and displacement increase simultaneously. This allows the range of $20\text{--}25^\circ$ to be regarded as the region providing the most rational combination of the investigated characteristics within the adopted numerical formulation. The selection of a specific angle within this range should depend on which criterion is more important for the design problem: limiting displacement or reducing the maximum stress level.

The observed variation in mechanical response is associated with changes in the geometric configuration and the mechanism of external load transfer through the top-member elements and the central hinged connection. Recent studies show that the deformation behaviour of support systems strongly depends on the stress state of the rock mass, the distribution of external loading, and the ability of the support to redistribute load [36], [37]. However, the present study did not include a separate determination of axial forces, bending moments, or their relative contributions to the overall stress state.

It should be taken into account that the performed modelling represents a comparative parametric study rather than a final design analysis of support for a specific mine working. When transitioning to real operating conditions, the coupled deformation of the support and surrounding rock mass, the actual stress state, geological structure, and spatial development of plastic zones should be considered, as confirmed by numerical and field studies of deep mine workings [36]–[38].

An additional limitation is the absence of a quantitative finite-element mesh-convergence study. Since the original ANSYS files containing several discretization variants were not available, the sensitivity of the maximum stress and displacement values to the finite-element size was not assessed. Therefore, the absolute calculated values should be interpreted

with this limitation in mind, whereas the main emphasis of the present study is placed on the relative comparison of geometric configurations calculated using the same modelling approach.

In addition, the considerable displacement levels obtained for configurations with larger inclination angles indicate the need to assess the effect of geometric nonlinearity in further studies. To move from comparative parametric analysis to practical design, it is advisable to account for nonlinear behaviour of the material and connections, interaction between the support and surrounding rock mass, actual mining and geological conditions, and realistic support conditions, while the numerical results should additionally be validated by experimental or field investigations [35], [37], [38].

4. Conclusions

The finite-element modelling performed in this study made it possible to establish the effect of the inclination angle of the top-member elements on the stress-strain state of the postless hinged support. It was shown that changes in the geometric configuration substantially affect both the maximum stress intensity and the magnitude of structural displacements.

For the baseline straight configuration under a control vertical load of 20 kN, the maximum stress intensity was 417.23 MPa and the maximum displacement was 115.8 mm. The transition to a two-element hinged structure led to a substantial reduction in maximum stress intensity throughout the investigated angle range. At $\alpha = 20^\circ$, 25° , 30° , and 35° , the corresponding values were 184.17, 176.77, 192.91, and 236.10 MPa, respectively. The minimum value was obtained at $\alpha = 25^\circ$, corresponding to a reduction of 57.6% relative to the straight configuration.

The variation in maximum displacement followed a different trend. Among the hinged configurations, the minimum value of 168.6 mm was obtained at $\alpha = 20^\circ$. With a further increase in the angle, the displacement increased to 185.1 mm at 25° , 220.9 mm at 30° , and 293.2 mm at 35° . Relative to the 20° configuration, these increases were 9.8%, 31.0%, and 73.9%, respectively. This indicates a progressive increase in the compliance of the hinged structure as the inclination angle of the elements increases.

The combined analysis of the absolute and normalized parameters confirmed that the most favourable inclination angles according to the two criteria do not coincide. At $\alpha = 20^\circ$, the minimum deformability among the hinged configurations is achieved, whereas at $\alpha = 25^\circ$, the minimum maximum stress intensity is obtained. When the angle exceeds 25° , both stress intensity and displacement increase simultaneously; therefore, a further increase in inclination provides no additional benefit within the adopted numerical formulation.

Considering the investigated criteria jointly, the range $\alpha = 20\text{--}25^\circ$ can be regarded as rational for the considered numerical scheme of the postless hinged support. An angle of 20° is preferable when displacement limitation is the priority, whereas 25° provides the most favourable stress state. The selection of a specific value within this range should be determined by the allowable deformation level and the actual strength requirements imposed on the support.

The obtained results should be regarded as a basis for further development of the support design. For practical design applications, it is necessary to account for the interaction within the “rock mass-support” system, actual

support conditions, real mechanical properties of the material, possible geometric and material nonlinearities, and to perform additional experimental or field validation of the numerical results.

Author contributions

Conceptualization: MB, ZR, AI; Data curation: ZA, ZR, AG; Formal analysis: ZA, NM, GB, AG; Funding acquisition: MB, AI; Investigation: ZA, AI; Methodology: MB, ZR, AI; Project administration: ZA, GB, AG; Resources: ZR, AI; Software: ZA, GB, AG; Supervision: MB, AI; Validation: ZA, ZR; Visualization: ZA, MB, NM; Writing – original draft: AI, AG; Writing – review & editing: ZA, MB, AI. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Чисельна оцінка та обґрунтування раціональної геометрії безстоякового шарнірного кріплення підготовчих гірничих виробок

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Мета. Визначення раціонального діапазону кутів нахилу елементів безстоякового шарнірного кріплення підготовчих підземних гірничих виробок на основі кількісної оцінки їхнього впливу на напружено-деформований стан конструкції.

Методика. У програмному комплексі ANSYS виконано порівняльне скінченно-елементне моделювання прямолінійного горизонтального верхняка ($\alpha = 0^\circ$) та двоелементних шарнірних конструкцій із кутами нахилу $\alpha = 20, 25, 30$ і 35° . Розрахунки проводилися у статичній лінійно-пружній постановці за однакових механічних характеристик матеріалу та контрольного вертикального навантаження 20 кН. Для кожного варіанта аналізувалися розподіл переміщень та інтенсивності напружень. Порівняльна оцінка виконувалася за максимальною інтенсивністю напружень, максимальним переміщенням, а також нормованими та відносними показниками їх зміни.

Результати. Для прямолінійної схеми максимальна інтенсивність напружень становила 417.23 МПа за максимального переміщення 115.8 мм. Перехід до шарнірної геометрії суттєво знизив максимальну інтенсивність напружень: до 184.17 МПа при 20° , 176.77 МПа при 25° , 192.91 МПа при 30° і 236.10 МПа при 35° . Мінімальне значення отримано при $\alpha = 25^\circ$, що відповідає зниженню на 57.6% відносно прямолінійної схеми. Водночас серед шарнірних варіантів максимальне переміщення послідовно зростало від 168.6 мм при 20° до 293.2 мм при 35° . Таким чином, мінімальні значення напружень і переміщень досягаються за різних кутів нахилу.

Наукова новизна. Встановлено немонотонну залежність максимальної інтенсивності напружень від кута нахилу елементів шарнірного верхняка за одночасного збільшення переміщень зі зростанням кута. Показано, що найбільш сприятлива геометрія за критерієм напруженого стану не збігається з найбільш сприятливою за деформаційним критерієм, що обґрунтовує спільне використання обох показників під час вибору геометричних параметрів кріплення.

Практична значимість. Для прийнятих умов навантаження та розрахункової постановки діапазон $\alpha = 20$ - 25° визначено як раціональний: при 20° забезпечується мінімальне переміщення серед досліджених шарнірних варіантів, тоді як при 25° досягається мінімальна максимальна інтенсивність напружень. Отримані результати можуть використовуватися як попередня основа для вибору геометрії кріплення перед виконанням комплексного моделювання взаємодії системи “масив гірських порід – кріплення” та подальшою експериментальною або натурною верифікацією.

Ключові слова: гірничі виробки; кріплення; шарнірне кріплення; метод скінченних елементів; напружено-деформований стан; чисельне моделювання

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