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JUSTIFICATION OF PARAMETERS FOR COMBINED SUPPORT OF DEEP UNDERGROUND EXCAVATIONS BASED ON THE ASSESSMENT OF THE SYNERGISTIC EFFECT OF THEIR INTERACTION

Abstract. The object of the study is the processes of ensuring the geotechnical stability of deep preparatory and capital mining excavations operating under conditions of intense rock pressure at depths exceeding 600–800 meters. A complex synergistic system is considered, which includes a structurally heterogeneous rock mass and combined multi-level support consisting of short steel rock bolts and long flexible cable anchors.

The problem solved in the work is due to a sharp decline in the efficiency of traditional support schemes when moving to deep horizons. Under high stress conditions, the individual load-bearing characteristics of support elements are unable to ensure the integrity of the excavation contour. The main disadvantage of existing approaches is the lack of coordination in the operation of different types of anchors, leading to their step-by-step failure and significant deformation of the mass.

This required quantitative assessment of the interaction of support elements to create a unified protective system. The essence of the results lies in establishing fundamental regularities of the joint operation of short and long anchors and introducing the scientific concept of the "synergy coefficient." The authors justified the rational support parameters: installation step 0.8×0.9 m, bolt length 2.4 m (tension 60–80 kN), and cable anchor length 7.3 m (tension 300 kN). Reliability of the results was confirmed by field tests at the Xin'an mine (horizon -600 m), where the error between numerical modeling and monitoring did not exceed 8.5%, and excavation convergence significantly decreased.

Maximum efficiency is achieved when the effective action boundary of short bolts exactly coincides with the beginning of the long cable anchors' fixation zone. This forms a continuous reinforced zone of large thickness, which transforms the surrounding rock mass from a source of load into a self-supporting structure, preventing rock stratification at the boundary of different support types. The balanced configuration provides a 67% reduction in convergence compared to the unsupported state at a material cost of approximately 380 USD per meter of advance.

The practical use of the results covers the design and construction of underground structures at coal and ore mines at depths over 600 m. The proposed solutions are effective for massifs with complex stress states and a tendency toward large plastic deformations.

Keywords: deep mining excavations, rock bolt, cable anchor, synergistic interaction, numerical simulation, material cost optimization MathCAD, rock mass stability.

1. Introduction

Due to the limited availability of easily accessible coal deposits, mining operations are forced to move deeper into the earth's interior. Many coal mines in China are currently extracting resources from depths exceeding 800 meters. It is expected that mining depths will exceed 1,000 meters within the next ten years [1, 2, 3]. As depth increases, the mechanical environment shifts from relatively safe shallow-level conditions to a highly complex scenario known as "three highs and one disturbance." This includes high geostress (typically ranging from 20 to 40 MPa), high geothermal temperature (usually exceeding 35°C), high karst water pressure in certain geological formations, and stress disturbances caused by mining activities, which can double or triple the initial in-situ stress values [4, 5, 6, 7]. Under such unfavorable conditions,

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the rock mass around deep roadways behaves quite differently. The plastic zone is extensive and continuously expanding. The roof may sag, the floor may heave, and the ribs may converge, potentially leading to the failure of the excavation (Fig. 1). If these issues are not addressed, the effective cross-sectional area can decrease by nearly 50% just a few months after excavation [8, 9].

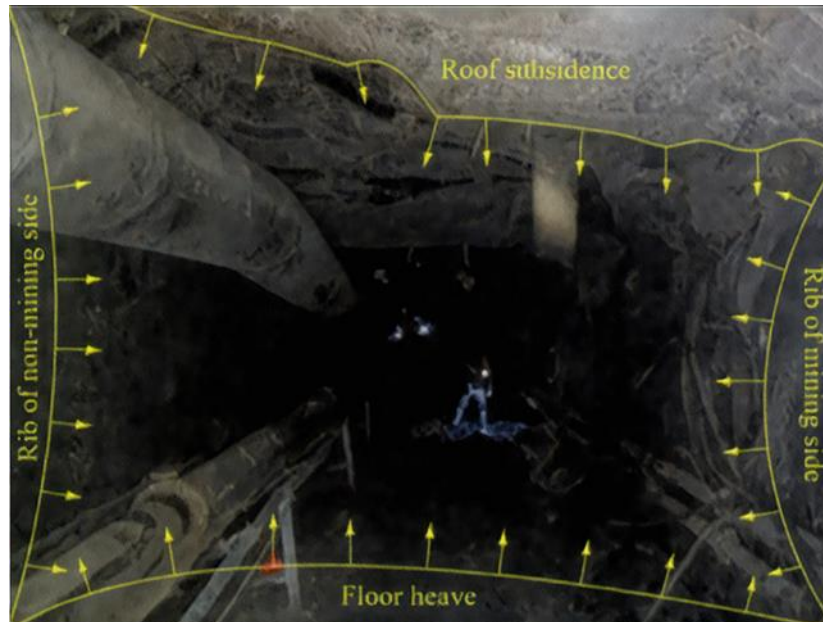


Figure 1 – Field observations of primary support performance in a ventilation roadway after installation. Yellow lines and arrows indicate the main deformations of the excavation contour

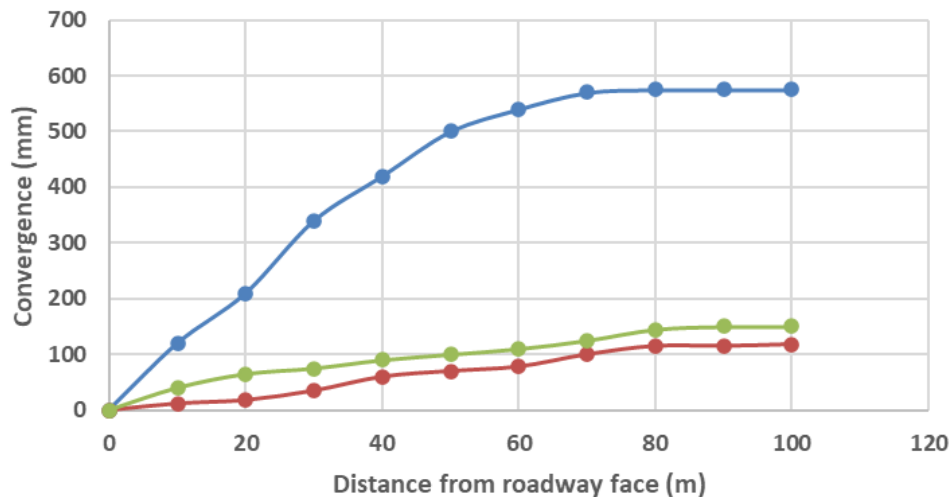
Following the excavation and under the influence of rock pressure, the surrounding rock mass undergoes intensive deformation, manifesting as roof subsidence, floor heave, and rib convergence. These deformation processes indicate stress redistribution in the boundary zone and a gradual loss of stability of the exposed rock surfaces.

Fig. 2 presents the results of field observations of excavation deformations as a function of the distance from the face. The x-axis represents the distance from the working face (m), and the y-axis represents the deformation value (convergence, mm). Curve 1 characterizes rib-to-rib convergence, Curve 2 represents roof subsidence, and Curve 3 represents floor heave.

Analysis of the graph shows that rib-to-rib convergence reaches the highest values. Curve 1 increases most intensively and reaches approximately 570–580 mm at a distance of about 80–100 m from the face. This indicates that the decisive manifestation of stability loss under the studied conditions is the lateral compression of the excavation; furthermore, rib deformations develop faster and exhibit significantly higher intensity compared to roof and floor deformations.

Floor heave is more pronounced than roof subsidence. Specifically, the deformation values according to Curve 3 reach approximately 150–160 mm, while for Curve 2, roof subsidence is about 110–120 mm. This indicates a significant role of floor deformations; however, their intensity remains lower compared to rib-to-rib convergence.

It has been established that deformations accumulate as the distance from the face increases. In the immediate vicinity of the face, the values are negligible; however, they gradually increase as the mining front advances and stress redistribution develops within the rock mass. The most intensive growth in deformations is observed within the range of approximately 10–70 m from the face. After 80 m, all curves gradually reach a plateau, indicating the completion of the primary deformation stage and the transition of the excavation into a state of relative stabilization. At the same time, this stabilization is achieved in the presence of significant residual deformations.



blue curve – rib-to-rib: rib convergence; green curve – floor heave;
red curve – roof subsidence

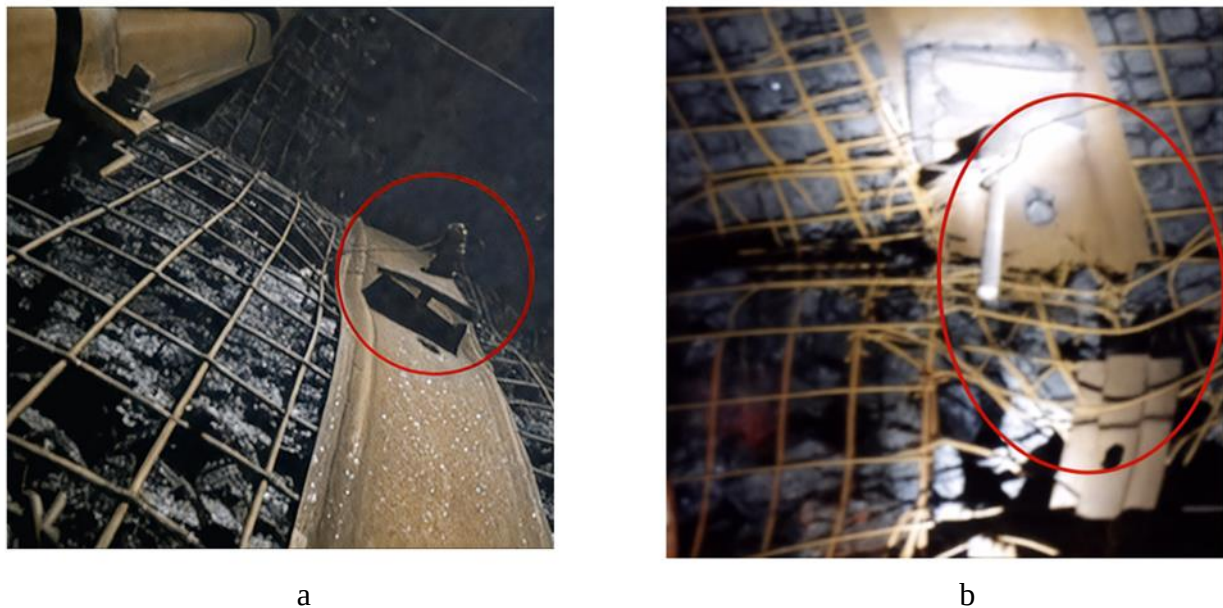
Figure 2 – Excavation deformation curves as a function of distance from the face

The obtained field observation results indicate the insufficient efficiency of the primary support system under the considered mining and geological conditions. Substantial rib convergence, floor heave, and roof subsidence confirm that the existing primary support does not ensure adequate excavation stability and requires improvement through the justification of a more effective combined support system.

2. Methods

The integrated "bolt-cable" support system is currently the most widely used method for stabilizing deep excavations. There are numerous reasons why this method is superior to traditional passive support methods, such as U-shaped steel arches and concrete lining (Fig. 3). This is achieved through the use of prestressed reinforcing elements to transfer the self-supporting capacity of the rock to deeper, more stable layers [10, 11].

The core idea of synergistic support lies in the simultaneous provision of two support types. The first zone is a shallow compression area created by rock bolts. This enhances the strength of the surrounding rock and makes it less prone to displacement.



(a) bolt pull-out/fallout; (b) steel strap rupture under excessive deformation

Figure 3 – Typical failure modes in support systems of deep excavations

The second zone is a deeper anchoring region where cable anchors transfer heavy loads to stable strata unaffected by the excavation. This renders the structure significantly stronger than its individual components [12, 13]. Although engineers frequently employ both bolts and cable anchors, the mechanism of their joint performance is not yet fully understood. This is particularly crucial for the quantitative evaluation of mutual reinforcement effects, identifying the optimal bolt layout for maximum synergy, and investigating how various geometric and mechanical factors influence the efficiency of composite support [6, 7].

Understanding the interaction between bolts and cables in deep excavations is challenging due to numerous factors: nonlinear bond-slip properties at the "bolt-grout" and "grout-rock" interfaces, gradual damage accumulation within the rock mass under prolonged high stress, rheological deformation of soft rocks, and dynamic stress redistribution caused by mining activities in adjacent faces [10, 8]. While traditional analytical methods provide fundamental insights into support mechanisms, they struggle to adequately capture the complexity of interrelated processes due to necessary simplifications regarding material homogeneity and boundary conditions [12]. Numerical modeling, specifically the finite difference method in FLAC3D and the discrete element method in PFC, has demonstrated high efficiency in predicting the mechanical behavior of anchored rock masses [8].

Recent advances in the numerical simulation of anchor behavior have focused on improving the constitutive representation of interface mechanics [12]. In FLAC3D, CABLE and PILE elements typically treat the interface as a perfectly elastic-plastic material. This fails to account for critical post-peak softening properties and residual strength [8]. Researchers have successfully integrated trilinear and biexponential bond-slip models using the FISH programming language. These models help align

numerical predictions with real-world observations, particularly regarding interface debonding and load redistribution [10].

When determining the optimal support parameters, it is essential to simultaneously consider efficiency, cost, and ease of installation [13]. Selecting parameters based solely on empirical experience can lead to either excessive material consumption or insufficient stability [12]. Modern optimization techniques, such as genetic algorithms, particle swarm optimization, and response surface methodologies, enable the identification of optimal parameter combinations [8]. The objective of this project is to utilize the results of numerical modeling and field studies to optimize support parameters for deep excavations at the -600 m horizon of the Xin'an mine (Shandong Province, China).

Preliminary modeling was conducted using FLAC3D software. Short rock bolts were treated as active reinforcement elements for the near-surface zone. Their primary function is to limit local stratification and rock shear, create a ring of increased stiffness around the excavation, and reduce the development rate of plastic deformations. Long cable anchors were modeled as deep reinforcement elements that transfer loads to more stable layers beyond the zone of intensive rock mass disturbance. Crucially, short bolts and long cable anchors are analyzed not in isolation but as interconnected elements of a unified support system.

A synergy coefficient was introduced for the quantitative analysis of mutual reinforcement between support elements. Its essence lies in comparing the effect of the system's joint performance with a linear superposition of the individual effects created by bolts and cable anchors separately. In practice, the synergy coefficient was determined by changes in average compressive stress, the increase in the thickness of the effective stress arch, and the reduction in excavation contour deformations compared to individual reinforcement schemes.

Table 1 – Calculated mechanical parameters of the main rock types

Rock type	Density, kg/m ³	Deformation modulus, GPa	Poisson's ratio	Cohesion, MPa	Friction angle, deg	Tensile strength, MPa
Medium sandstone	2650	12.5	0.23	3.8	35	2.1
Siltstone	2580	8.3	0.26	2.5	32	1.4
Coal	1400	2.1	0.32	0.8	28	0.3
Sandy argillite	2520	6.5	0.28	2.0	30	1.0
Argillite	2450	4.2	0.30	1.2	26	0.6

Mechanical parameters of the rocks were assigned based on the results of geological and laboratory studies of the rock mass in the excavation area. The calculations included the primary lithological varieties forming the roof, surrounding rocks, and floor. Parameterization accounted for density, deformation modulus, Poisson's ratio, cohesion, internal friction angle, and tensile strength. Such detailed property assignment allows for the accurate reproduction of load heterogeneity and the character of plastic zone development.

The provided set of parameters reflects the contrast between the high-strength sandstones of the roof and the significantly weaker coal and argillites. This distinction is fundamentally important for the accurate reproduction of non-uniform stress redistribution and the formation of plastic zones. All parameters were utilized in a series of baseline and parametric numerical experiments.

3. Results and discussion

According to previous numerical modelling performed using FLAC3D software [1,3], it was found that short rock bolts form a near-contour zone of increased compressive stresses and reduced fracturing, extending to approximately 0.9 of the bolt length from the excavation contour. Within this specific zone, the most significant effect of pretensioning is observed: rock compaction is enhanced, the intensity of bedding separation is reduced, and the development of the plastic zone is decelerated. However, beyond the effective action limit of the short bolts, the stressing effect dissipates rapidly.

In contrast to rock bolts, long cable anchors have almost no effect on the stress state directly near the excavation contour. However, a stress redistribution zone is formed within their anchorage area. This zone becomes the load-bearing zone for the entire support system, as it ensures load transfer to more stable rock layers that have not been significantly weakened by excavation.

When both systems operate jointly, a zone of coordinated load transfer is formed between them. Within this zone, short bolts stabilize the weakened near-surface strata and create a stiffer medium for transferring the reaction from the cable anchors. In turn, the cable anchors prevent the bolt-reinforced near-surface zone from losing stability due to shear or excessive inward displacement. This dual-action mechanism constitutes the physical essence of the synergistic effect.

The synergy coefficient reached its maximum in the transition region between the effective action zone of the short bolts and the beginning of the long cable anchors' anchorage zone. For rational schemes, this coefficient ranged from 0.28 to 0.32, indicating a system efficiency increase of approximately 30% compared to a simple linear superposition of individual effects. The spatial distribution pattern of the synergy coefficient resembles an elongated shell around the excavation, most pronounced in the roof and the upper sections of the ribs.

Consequently, it has been established that the mechanism of joint performance between short rock bolts and long cable anchors is systemic in nature. It is realized through a combination of three processes: the formation of a near-surface compacted zone, the creation of a deep support region in the cable anchor anchorage zone, and continuous load transfer between them. This conclusion served as the basis for the subsequent optimization of support parameters.

The optimization of parameters for the combined support of a deep excavation was performed as a multi-criteria search for a rational configuration of short rock bolts and long cable anchors within the MathCAD environment. The objective of the optimization was to determine a set of support system parameters that ensures minimum excavation contour convergence, an acceptable support cost per 1 m of ad-

vance, and the maximum thickness of the effective compressive stress arch. This formulation allows for the simultaneous consideration of geomechanical efficiency, cost-effectiveness, and the structural feasibility of the system.

The decision variable vector was defined as:

$$x = [s_b, s_r, L_b, P_b, s_c, L_c, L_a, P_c]^T, \quad (1)$$

where s_b is the bolt spacing along the perimeter; s_r is the row spacing of bolts; L_b is the rock bolt length; P_b is the bolt pretension; s_c is the cable anchor spacing; L_c is the cable anchor length; L_a is the cable anchorage length; and P_c is the cable pretension.

The decision variables and their respective bounds are presented in Table 2, reflecting the practical ranges of support parameters for deep coal mines.

Table 2 – Decision variables and bounds for support parameter optimization

Variable	Symbol	Unit	Lower	Upper bound
Bolt spacing along the perimeter	s_b	m	0.6	1.2
Spacing between rows of bolts	s_r	m	0.7	1.2
Bolt length	L_b	m	2.0	3.0
Bolt pretension	P_b	kN	40	100
Cable anchor spacing	s_c	m	1.2	2.4
Cable anchor length	L_c	m	6.0	9.0
Anchorage length	L_a	m	1.5	3.5
Cable pretension	P_c	kN	200	400

The optimization process is subject to the following constraints:

Stability constraint: $\delta_{\max} \leq \delta_{\text{allow}}$ where $\delta_{\text{allow}} = 150$ mm for the investigated class of excavations, $\delta_{\max} > 0$.

Synergy constraint: $\eta_{\text{mean}} \geq 0.2$ which ensures optimal interaction between the rock bolt–cable anchor system, where η_{mean} is the mean value of the synergy index, or synergy coefficient.

Spacing constraint: $s_c \geq 2 s_b$ reflecting typical installation practices.

Length constraint: $L_c - L_a \geq L_b$, which guarantees that the cable anchorage zone begins beyond the active zone of the rock bolts.

The optimization problem was formulated as the minimization of the objective function vector: $\min F(x) = [f_1(x), f_2(x), f_3(x)]$ where:

$$f_1(x) = u_{\max}(x), \quad f_2(x) = C(x), \quad f_3(x) = -H(x),$$

and $u_{\max}$ is the maximum predicted excavation convergence; C is the support cost per 1 m of advance; and H is the thickness of the effective compressive stress arch.

The use of a negative value for H is necessitated by the fact that the overall problem was formulated as a minimization task, whereas the thickness of the stress arch required maximization.

In MathCAD, the multi-criteria problem was reduced to the minimization of a generalized objective function, represented as a weighted sum of normalized criteria:

$$\Phi(x) = \omega_1 \frac{u_{\max}(x)}{u_{\text{ref}}} + \omega_2 \frac{C(x)}{C_{\text{ref}}} - \omega_3 \frac{H(x)}{H_{\text{ref}}}, \quad (2)$$

where $\omega_1, \omega_2, \omega_3$ are the weighting coefficients of the criteria, and $u_{\text{ref}}, C_{\text{ref}}, H_{\text{ref}}$ are the reference normalization values. This approach allows for the analysis of variants with different criterion priorities within a single computational environment, generating solutions with a balanced, safety-oriented, or cost-effective emphasis.

The following constraints were accounted for during the problem-solving process:

$$u_{\max}(x) \leq 120 \text{ mm} \quad u_{\max}(x) > 0$$

$$\eta(x) \geq \eta_{\min}, \quad s_b \leq s_r, \quad L_c - L_a \geq 0.9L_b,$$

where $\eta(x)$ is the synergy index characterizing the combined performance of the support elements; $\eta_{\min}$ is the minimum allowable value of the synergy index.

The first constraint ensured excavation stability relative to the allowable convergence level. The second guaranteed significant synergistic interaction between the bolts and cable anchors. The third reflected the technological requirements for the anchor layout scheme. The fourth ensured that the cable anchorage zone begins outside the effective reinforcement zone of the short bolts.

In the practical MathCAD implementation, optimization was conducted using approximating response functions derived from prior numerical data, rather than directly executing full FLAC3D simulations at each iteration. To achieve this, an array of parameter variants x_i was established, for which the values of $u_{\max}, C, H$, and η were determined from FLAC3D results. Subsequently, second-order approximating dependencies were constructed in MathCAD: $u_{\max} = f_u(x), C = f_C(x), H = f_H(x), \eta = f_\eta(x)$ in the form of polynomial response surface models.

The general form of the response surface model was defined as:

$$f(x) = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n a_{ii} x_i^2 + \sum_{i=1}^n \sum_{j=i+1}^n a_{ij} x_i x_j, \quad (3)$$

where $f(x)$ denotes the approximated value of the target criterion; a_0 is the intercept term; a_i are the coefficients of the linear terms; a_{ii} are the coefficients of the quadratic terms; a_{ij} are the coefficients of the interaction terms between pairs of variables; x_i and x_j are the design variables; and n is the total number of variables.

The model coefficients were determined using the least squares method in matrix form:

$$\beta = (A^T A)^{-1} A^T Y(4),$$

where A is the factor matrix, Y is the response vector, and β is the vector of regression coefficients. These dependencies were subsequently employed for the rapid calculation of criterion values during the optimization procedure.

Based on the optimization results obtained using the presented equations in MathCAD, Table 3 shows the rounded values of the recommended support parameters for excavations at depths of 600–800 m. The recommended support layout parameters provide a 67% reduction in excavation convergence compared with the unsupported state, with material costs of approximately USD 380 per metre of advance.

Analysis of the obtained solutions shows that reducing bolt spacing and increasing the pretension level ensure the best control over deformations but are accompanied by a significant increase in cost. Conversely, increasing the spacing and reducing the length and tension of the cables decrease material consumption but lead to a deterioration in the condition of the surrounding rock mass and a reduction in the thickness of the compressive stress arch. The balanced variant occupies an intermediate position and provides the optimal ratio between reliability and cost, justifying its recommendation for practical application.

Table 3 – Recommended support parameters based on optimization results

Parameter	Recommended anchoring parameters	Safety Priority	Economy Priority
Bolt spacing (m)	0.80	0.70	1.00
Row spacing (m)	0.90	0.80	1.00
Bolt length (m)	2.40	2.60	2.20
Bolt pretension (kN)	65	80	50
Cable spacing (m)	1.60	1.40	2.00
Cable length (m)	7.30	8.00	6.50
Anchorage length (m)	2.50	2.80	2.20
Cable pretension (kN)	300	350	250
Predicted convergence (mm)	68	52	95
Support cost (USD/m)	380	520	290
Arch thickness (m)	5.8	6.4	4.9

Engineering validation of the results. The Xin'an mine is located in the North China Coal Basin. The working horizons are at a depth of – 600 m, which corresponds to a vertical stress of approximately 15 MPa and a horizontal stress of 18 MPa (determined by the hydraulic fracturing method). The main roadway was driven through layers of medium-grained sandstone (12 m roof), siltstone (3 m immediate roof), a coal seam (5.8 m), and argillite (4 m floor). The roadway cross-section is 5.0 m wide and 3.8 m high.

The support system was installed in accordance with the balanced configuration: roof bolts Ø22×2400 mm (spacing: 800×900 mm, tension: 60–65 kN); rib bolts with similar parameters; and roof cable anchors Ø21.8×7300 mm (spacing: 1600×1800 mm, tension: 280–300 kN). W-shaped steel straps were also used to enhance surface

support. The support system was installed at a distance of no more than 20 m from the face.

Monitoring data over a six-month period (Table 4) showed a high degree of correlation with numerical predictions. The maximum roof subsidence was 62 mm, which is only 8.8% less than the predicted 68 mm. The slight underestimation of the prediction in the model is attributed to conservative estimates of the rock mass strength parameters, which establishes a necessary safety margin during the design process.

Extensometer data confirmed that approximately 75% of the roof displacements occurred within the first 3 meters (the bolt-reinforced zone). This validates the effectiveness of the selected scheme: the rock bolts stabilize the immediate surrounding rock, while the cable anchors reliably tie this zone to the deep stable strata.

Table 4 – Comparison of monitoring and predicted values

Parameter	Prediction	Measured	Difference
Roof subsidence (mm)	68	62	-8.8%
Floor heave (mm)	45	51	+13.3%
Rib convergence (mm)	85	78	-8.2%
Max. bolt load (kN)	125	118	-5.6%
Max. cable load (kN)	420	385	-8.3%
Roof delamination at 3 m (mm)	12	9	-25.0%

To evaluate the advantages of the optimized combined support system, the performance indicators of the experimental excavation were compared with an adjacent section where standard support parameters based on empirical design were employed. Prior to the study, the standard support involved bolt installation with a 1.0 m×1.0 m grid (40 kN tension) and cable anchors with a 2.0 m×2.0 m grid (200 kN tension).

The comparison demonstrated that the optimized system provides significantly better deformation control. Roof subsidence was reduced by 67.3% (from 189 mm to 62 mm), rib convergence by 58.9% (from 190 mm to 78 mm), and floor heave by 43.2% (from 90 mm to 51 mm). These improvements were achieved with a material cost increase of only 32%, indicating substantially higher economic efficiency of the optimized configuration compared to the standard one (Table 5).

Table 5 – Generalized results of support parameter optimization

Configuration	Convergence, mm	Cost, USD/m	Arch thickness, m
Balanced	68	380	5.8
Safety priority	52	520	6.4
Economy priority	95	290	4.9

4. Conclusions

Quantitative regularities of the synergistic interaction between short rock bolts and long cable anchors in the support system of deep excavations have been established. Based on numerical modelling in FLAC3D and multi-criteria optimization in MathCAD, a rational support configuration was determined for great-depth conditions of 600–800 m.

The main result is the solution of the optimization problem for selecting anchoring support parameters, based on maximizing the synergy coefficient while minimizing deformation and cost.

The high efficiency of the system is attributed to the mechanical integration of "nested" rock mass reinforcement zones. Short bolts improve the properties of the immediate surrounding rock, creating a bearing base for load transfer to the long cable anchors, which in turn secure the entire reinforced zone deep within the massif. The highest synergy coefficient (0.28–0.32) is achieved at "zero overlap," where the reinforcement limit of the short bolts coincides with the beginning of the cable anchor's anchorage zone. This ensures continuous and uniform stress transfer without excessive over-reinforcement or ruptures within the rock mass.

This study expands the geomechanical understanding of combined support systems by introducing a mathematical framework for evaluating the interaction between different anchor types. Future development vectors have been identified, including the integration of rheological processes and machine learning methods for real-time optimization.

Mining engineers are provided with ready-to-use design solutions for deep horizons. Parameter sensitivity analysis allows for a focus on the most critical factors (bolt spacing and tension) to control convergence while simultaneously optimizing economic indicators (cable anchor expenditures). Field validation at the Xin'an mine confirmed the reliability of the predictions, with an error margin of less than 10%.

Future research directions will involve expanding the optimization framework to account for time-dependent rheological behavior under prolonged high stress, integrating dynamic load effects resulting from mining-induced seismicity, and developing surrogate machine learning models to facilitate real-time support design optimization based on continuously updated monitoring data.

Conflict of interest

Authors state no conflict of interest.

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ОБҐРУНТУВАННЯ ПАРАМЕТРІВ КОМБІНОВАНОГО КРІПЛЕННЯ ГЛИБОКИХ ВИРОБОК НА ОСНОВІ ОЦІНКИ СИНЕРГЕТИЧНОГО ЕФЕКТУ ЇХНЬОЇ СУМІСНОЇ РОБОТИ

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Анотація. Об'єктом дослідження є процеси забезпечення геотехнічної стійкості глибоких підготовчих і капітальних гірничих виробок, що експлуатуються в умовах інтенсивного гірського тиску на глибинах понад 600–800 м. Розглядається складна синергетична система, яка включає структурно неоднорідний гірський масив і комбіноване багаторівневе кріплення, що складається з коротких сталевих породних анкерів і довгих гнучких канатних анкерів.

Проблема, розв'язана в роботі, зумовлена різким зниженням ефективності традиційних схем кріплення при переході до глибоких горизонтів. В умовах високих напружень індивідуальні несучі характеристики елементів кріплення не здатні забезпечити цілісність контуру виробки. Основним недоліком існуючих підходів є відсутність узгодженості в роботі різних типів анкерів, що призводить до їх поетапного руйнування та значних деформацій масиву.

Це зумовило необхідність кількісної оцінки взаємодії елементів кріплення для створення єдиної захисної системи. Сутність отриманих результатів полягає у встановленні фундаментальних закономірностей спільної роботи коротких і довгих анкерів та введенні наукового поняття «коефіцієнт синергії». Авторами обґрунтовано раціональні параметри кріплення: крок встановлення 0,8×0,9 м, довжина анкера 2,4 м (натяг 60–80 кН) та довжина канатного анкера 7,3 м (натяг 300 кН). Достовірність результатів підтверджено натурними випробуваннями на шахті Xín'ān (горизонт –600 м), де похибка між числовим моделюванням і моніторингом не перевищувала 8,5%, а зближення контуру виробки суттєво зменшилося.

Максимальна ефективність досягається тоді, коли межа ефективної дії коротких анкерів точно збігається з початком зони закріплення довгих канатних анкерів. Це формує суцільну армовану зону значної потужності, яка перетворює навколишній гірський масив із джерела навантаження на самонесучу конструкцію, запобігаючи розшаруванню порід на межі дії різних типів кріплення. Збалансована конфігурація забезпечує зменшення зближення контуру на 67 % порівняно зі станом без кріплення за матеріальних витрат близько 380 дол. США на 1 м проходки.

Практичне використання результатів охоплює проєктування та будівництво підземних споруд на вугільних і рудних шахтах на глибинах понад 600 м. Запропоновані рішення є ефективними для масивів зі складним напруженим станом і схильністю до великих пластичних деформацій.

Ключові слова: глибокі гірничі виробки, породні анкери, канатні анкери, синергетична взаємодія, числове моделювання, оптимізація матеріальних витрат, MathCAD, стійкість гірського масиву.