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Hoang Hung Thang
Quang Ninh University of
Industry, Quang Ninh,
Vietnam

Do Xuan Huynh
Quang Ninh University of
Industry, Quang Ninh,
Vietnam

Research on the influence of prestress on the formation of rock mass reinforcement arch around coal mine roadways

Hoang Hung Thang and Do Xuan Huynh

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Abstract

The transition to deep-level mining below -200 m in Vietnam's coal sector, particularly at the Mao Khe mine, necessitates a shift from passive support systems to active reinforcement strategies to counteract high strata pressure and complex rock deformation. This study utilizes FLAC3D numerical simulation with a Mohr-Coulomb constitutive model to quantitatively analyze the formation of a "Reinforcement Arch" in medium-stability sandstone ($f=4-6$) under varying bolt prestress levels. The results demonstrate that a prestress level of 60 kN is the optimal threshold; at this value, the individual compression zones around each bolt effectively intersect to form a continuous, stable load-bearing structure with a thickness of 0.9-1.2 m. This active arch successfully restricts the expansion of the plastic zone from 1.2 m to 0.45 m and reduces roof displacement by 24.5%, providing a scientifically grounded approach to optimizing support costs while ensuring maximum underground safety.

Keywords: Reinforcement Arch, Prestressed Rock Bolts, FLAC3D Simulation, Deep Mining Stability

1. Introduction

In contemporary Vietnamese underground coal mining, as shallow coal seams are gradually being depleted, mines are simultaneously transitioning to deeper levels (below -200 m). Maintaining the stability of deep-level roadways faces significant challenges due to high strata pressure and complex surrounding rock deformation, particularly under the varying geological conditions of the Quang Ninh region. Traditional support methods using rigid steel sets, while possessing high load-bearing capacity, are inherently "passive", they only begin to resist pressure after the rock mass has already fractured and loosened. This results in high maintenance costs and significant safety risks. According to [1], the combined support system of Rock Bolts - Wire Mesh - Shotcrete marks a pivotal shift toward "active" support methods, which focus on mobilizing the self-supporting capacity of the surrounding rock mass itself. The most critical link in this support technology is the prestressing force of the bolts. When a bolt is prestressed immediately after installation, it exerts a compressive force on the rock mass, shifting the stress state from tension or shear to multiaxial compression [2]. This compressive force significantly enhances the mechanical parameters of the rock, such as cohesion and the internal friction angle. When bolts are installed with an appropriate density, their residual compressive stress zones overlap, creating a continuous band around the roadway perimeter and forming a "Reinforcement Arch". This arch acts as a self-bearing structure, preventing the expansion of the plastic zone and preserving the integrity of the roadway [1].

Globally, the reinforcement arch theory has been extensively studied by numerous scholars, focusing on the concept of bolted rock mass stability within the surrounding strata [3, 4]. This study approaches the problem using a Mohr-Coulomb perfect plasticity model within a finite difference environment [5, 6]. The selection of this model enables a realistic simulation of the plastic zone formation and stress redistribution processes under the influence of bolt prestressing force [7]. In Vietnam, numerous studies have demonstrated the effectiveness of prestressed rock bolts in replacing traditional steel sets. However, the majority of current research typically focuses on either ideal geological conditions (high-strength rock) or highly specific cases (such as weak roof strata within coal seams [1, 8]).

Corresponding Author:
M Baskaran
Hoang Hung Thang
Quang Ninh University of
Industry, Quang Ninh,
Vietnam

Although the role of prestress has been widely recognized, determining the 'optimal' prestress level to form an effective reinforcement arch remains an open question under the specific conditions of the -230 m level cross-cut roadways at Mao Khe coal mine, where the rock mass possesses medium stability ($f=4-6$) and a lithological composition of interbedded sandstone and siltstone. Practical construction experience indicates that if the prestress is too low (< 20 kN), the reinforcement arch fails to connect continuously, leading to roof sagging or localized falls. Conversely, excessively high prestress (> 100 kN) results in extreme stress concentration at the bolt head, damaging the shotcrete layer and causing bolt failure at the threaded section. The lack of quantitative guidelines regarding the relationship between prestress and reinforcement arch thickness is a major barrier to design optimization [9]. While traditional calculation methods, such as those by Protodyakonov or Terzaghi, established the foundation for determining strata pressure, these approaches often treat the rock mass as a discrete medium and the support force as passive [10, 11]. In the deep mining conditions at Mao Khe, relying solely on empirical formulas while ignoring the dynamic interaction between bolt prestress and the self-strengthening capacity of the rock mass ($f=4-6$) leads to inaccurate designs [1]. The current research gap lies in establishing a quantitative relationship between specific prestress values and the thickness of the Pre-stressed Reinforcement Arch to minimize costs while ensuring absolute safety. Based on the issues, this paper focuses on utilizing numerical simulation with FLAC3D software to quantitatively analyze the influence of different prestress levels on the formation of the reinforcement arch. The objectives of this research are: (1) To clarify the evolution of the plastic zone under the impact of various prestress levels. To determine the optimal prestressing force for sandstone with a stability coefficient of $f=4-6$; (2) To validate the results through in-situ monitoring data from the construction site; (3) The research findings not only contribute to refining the theoretical framework of the reinforcement arch but also offer high practical value in ensuring safety and reducing support costs for the Mao Khe coal mine in particular, and the Vietnamese underground coal mining industry in general.

2. Study Area

The direct object of this research is the Southwest I cross-cut roadway at the -230 m level, part of the investment project for deep-level mining below -150 m at the Mao Khe coal mine. This is a vital roadway serving transportation and ventilation for the mine's Southwest sectors. The roadway features an arch-shaped design with an excavation cross-sectional area of 9.5 m^2 , a clear width of 3.4 m, and a height of 3.0 m. The lithological characteristics of this area are relatively complex, with interbedded sedimentary rock layers: Main composition: Primarily light gray sandstone, ranging from fine to medium-grained, interbedded with dark gray siltstone layers. Fracture state: The rock mass is moderately fractured; the fissures are often filled with weak argillaceous or silty materials, which reduces the continuity of the rock mass. Stability: The average stability coefficient (f) of the rock mass ranges from 4 to 6. This type of rock has medium strength but is susceptible to deformation and instability when subjected to strata pressure at great depths. At the -230 m level, the roadway is affected by in-

situ stress caused by the weight of the overlying strata. With an average depth of 250 m to 300 m, the static pressure in this area is estimated at approximately 6.5-7.5 MPa. These pressure conditions, combined with the geomechanical properties of the rock ($f = 4-6$), make the roadway perimeter prone to the formation of a plastic zone (failure zone) if bolt prestress is not applied promptly to form an active reinforcement arch. To ensure the objectivity and reliability of the numerical model, the input parameters for the geomechanical properties of the sandstone ($f = 4-6$) at the -230 m level of Mao Khe mine were synthesized from field rock sample testing results and are presented in detail in Table 1.

Table 1: Geomechanical properties of rock mass and support materials for numerical simulation

Parameters	Symbol	Unit	Value
Unit weight	γ	kN/m ³	26.5
Elastic modulus	E	GPa	1.85
Poisson's ratio	μ		0.25
Cohesion	C	MPa	1.25
Internal friction angle	ϕ	Degree	32
Uniaxial compressive strength	σ_c	MPa	45.0
Tensile strength	σ_t	MPa	1.20

3. Methodology

This study combines theoretical rock mechanics with modern numerical simulation methods to quantitatively analyze the formation of the reinforcement arch.

3.1. Theoretical basis of the reinforcement arch

Based on the perspectives of international scholars and research in Vietnam, the methodology is founded on the following hypothesis: When a rock bolt is prestressed, it generates a residual compressive stress zone within the rock mass. If the bolt spacing (a) and bolt length (L) are designed appropriately, these compressive zones will overlap. The thickness of the reinforcement arch (h_v) is determined by the intersection of these compressive stress zones, creating a closed arch-like structure capable of bearing strata loads transmitted from the surrounding rock mass.

3.2. FLAC3D numerical simulation method

To quantify the impact of prestress, the study employs FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) software. This is a specialized program based on the finite difference method, allowing for the accurate simulation of the plastic deformation and failure processes of the rock mass.

3.2.1. Numerical Model Setup

- **Model dimensions:** The model is established with dimensions of $50 \text{ m} \times 50 \text{ m} \times 1 \text{ m}$ (length $\times$ height $\times$ thickness) to eliminate the influence of boundary effects.
- **Element meshing:** The rock mass is divided into zones (solid elements). The area surrounding the roadway is refined with a finer mesh to observe the stress variations and the failure zone in detail.
- **Boundary conditions:** Horizontal displacements are restricted at the lateral sides (roller boundaries), and the bottom of the model is fully fixed (fixed boundary).

Based on actual field parameters, the numerical model is

established with the roadway cross-section and the layout of support elements (bolts, shotcrete) as described in Figure 1.

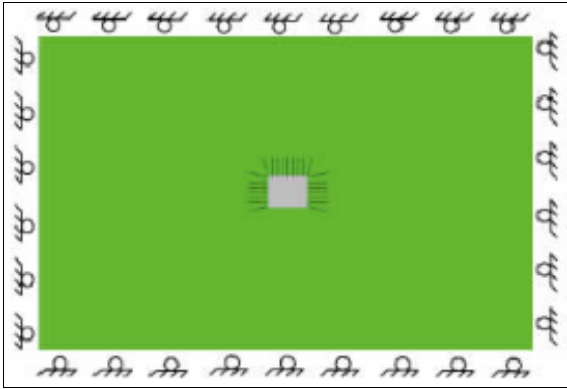


Fig 1: Cross-sectional diagram of the numerical model

To ensure the convergence and accuracy of the FLAC3D numerical model, the interaction parameters for the Cable elements (rock bolts) were detailed as follows: the bond stiffness was set at 1.5×10^9 N/m, and the interface bond cohesion between the grout and the rock was assigned a value of 52.8 kN, based on in-situ pull-out test results. The Mohr-Coulomb constitutive model was selected to focus on analyzing the changes in the residual compressive stress state without overcomplicating the problem with strain-softening variables.

3.2.2. Constitutive models and support elements rock mass

The Mohr-Coulomb perfect plasticity model is utilized, with geomechanical parameters specified in Table 1. Support elements: Cable elements are employed to simulate the rock bolts. The specifications include D20 steel bolts with a length of 2.2 m, and a grid spacing (both row spacing and bolt spacing within a row) of $0.8 \text{ m} \times 0.8 \text{ m}$. Prestressing force (Pt): This is assigned to the cable elements immediately upon installation in the model, accurately simulating the hydraulic tensioning process applied at the Mao Khe mine site.

3.3. Simulation Procedure

The simulation process is conducted through four main steps to closely replicate actual construction practices:

- **Step 1:** Establishment of in-situ stress state. Initializing the virgin stress state of the rock mass at the -230 m level (corresponding to the hydrostatic pressure γH).
- **Step 2:** Roadway excavation simulation. Removing elements within the roadway perimeter. At this stage, the rock mass begins to deform, and the plastic zone initiates.
- **Step 3:** Installation of support systems. Implementing rock bolts and shotcrete. The design prestressing force is assigned to the cable elements.
- **Step 4:** Solving to equilibrium. Running the model until it reaches force equilibrium (with a convergence criteria of 10^{-5} or 10^{-6}).

3.4. Evaluation Criteria

To evaluate the formation of the reinforcement arch, the following indicators are extracted from the model: Axial compressive stress distribution along the bolt: To determine the overlap between compression zones.

Plastic zone dimensions: To evaluate the extent of failure zone reduction as prestress increases.

Roof and sidewall displacement: To quantify the deformation control effectiveness of the reinforcement arch.

4. Results and Discussion

4.1. Influence of Prestressing Force

When the prestressing force varies in the case of a single rock bolt installed in the roof, the distribution of the reinforced compressive stress in the roof is illustrated in Figure 2.

The following observations are drawn from the analysis of Figure 2:

As the prestressing force varies, the distribution pattern of stress along the bolt within the rock mass remains consistent, following a specific rule: stress concentration reaches its peak at the bolt tail (at the roadway perimeter); subsequently, the compressive stress gradually diminishes with depth into the rock mass. At a depth of approximately 3/4 of the bolt length from the perimeter, the stress decreases to zero and transitions into a tensile stress zone toward the bolt head (the deeper part of the rock mass).

As the prestress increases, both the magnitude and the extent of the reinforced compressive stress zone increase accordingly. Furthermore, the transition zone where the stress value is approximately zero between the compressive and tensile regions tends to narrow, indicating an enhanced efficiency in rock mass reinforcement by the bolting system.

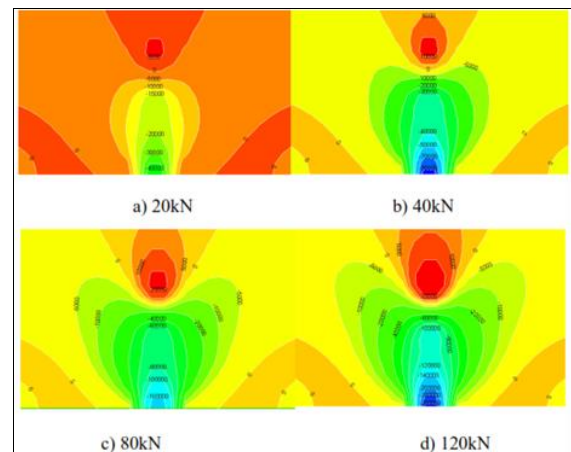


Fig 2: Distribution of reinforced stress in the roof for a single rock bolt under different

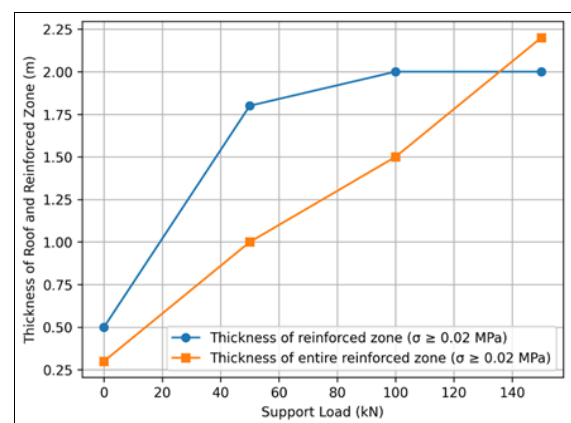


Fig 3: Relationship between prestressing force and the thickness and width of the reinforced stress zone with values exceeding 0.02 MPa

Figure 3 illustrates the influence of anchor pre-stress levels on the development of the compressive stress zone (values > 0.02 MPa). As the pre-stress increases from 20 kN to 40 kN, the thickness of this compressive zone expands significantly by 2.16 times. However, beyond this threshold, further increases in pre-stress result in a marginal thickness increment of only 0.18 m. In contrast to the thickness stabilization, the width of the stress zone increases progressively with higher pre-stress levels, exhibiting a near-linear correlation.

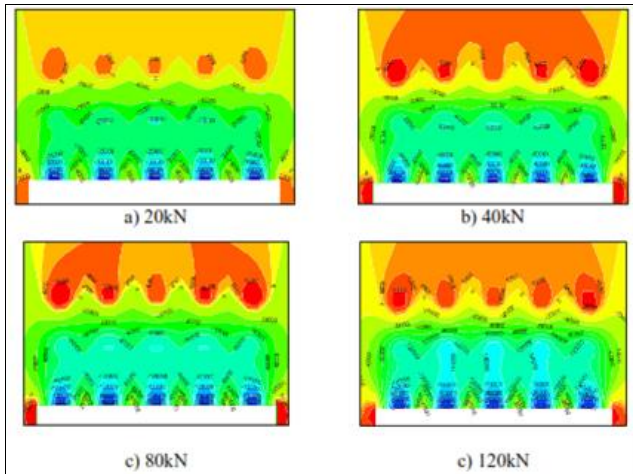


Fig 4: Distribution of reinforcement stress in the roof for 5-bolt installation under different pre-stress levels.

Figure 4 and Figure 5 demonstrate that with a 5-bolt reinforcement pattern, the mutual interaction between compressive stress zones effectively binds the rock mass into a cohesive, load-bearing reinforcing arch. Specifically, at a pre-stress level of 20 kN, the compressive stress in the arch is only 0.02 MPa, whereas at 120 kN, it increases to 0.12 MPa. When the pre-stress is set at 20 kN, compressive stress zones ≥ 0.04 MPa appear in isolation with very

limited coverage, failing to interact between adjacent bolts. In this state, large areas of low stress predominate, preventing the formation of a continuous reinforcing zone. However, as the pre-stress increases to 120 kN, these high-compression zones expand and fill the gaps between bolts, interconnecting to establish a solid reinforcing arch. Furthermore, the boundary compressive stress between bolts increases from 0.005 MPa to 0.02 MPa, significantly enhancing the stability of the tunnel periphery. Increasing the bolt pre-stress effectively expands both the thickness and width of the reinforcing arch beyond the tunnel span, which is highly beneficial for maintaining the long-term stability of the underground opening.

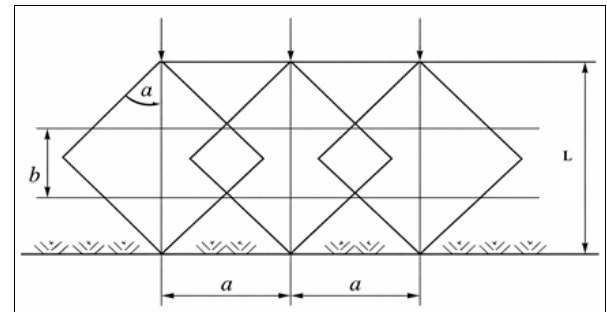


Fig 5: Mechanical model of the rock bolt reinforcing arch ^[12] (L- Bolt length, m; a- Bolt spacing, m; b- Thickness of the reinforcing arch; α - Rock control angle of the bolt, $\alpha=45^\circ$)

4.2. Evolution Law of the Plastic Zone

Numerical simulation results indicate a strong inverse correlation between the pre-stress level and the extent of the plastic zone. As the pre-stress (P_t) increases from 20 kN to 60 kN, the failure zone at the tunnel roof is compressed and significantly reduced from 1.2 m to 0.45 m. This demonstrates that the formation of a reinforcing arch effectively transitions the surrounding rock mass from a failure mechanism to an efficient self-supporting mechanism.

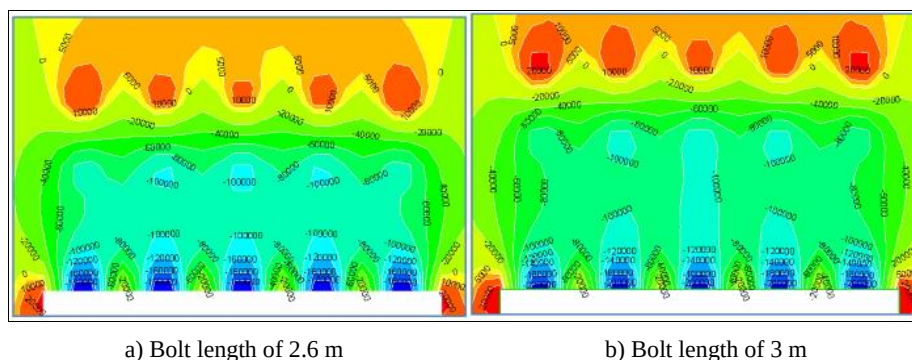


Fig 6: Distribution of reinforcing compressive stress in the roof under different bolt lengths

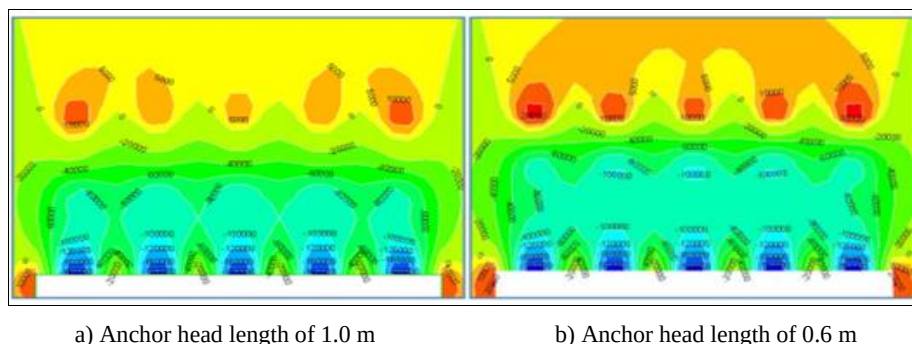


Fig 7: Distribution of reinforcing compressive stress in the roof under different anchor head lengths

4.3. Analysis of tunnel peripheral displacement

The effectiveness of the reinforcing arch is specifically quantified through the changes in roof and rib displacements.

Table 2: Illustrates a progressive reduction in displacement as the pre-stress level increases

Scenario	Pre-stress level Pt (kN)	Roof displacement (mm)	Rib displacement (mm)	Roof deformation reduction efficiency (%)	Compacted arch thickness hv (m)	Reinforcing arch status
1	20	147	81	-	< 0.4	Discontinuous and discrete
2	40	123	68	16.3%	0.6 - 0.8	Initial intersection / Commencement of overlap
3	60	111	61	24.5%	0.9 - 1.2	Continuous and stable
4	80	109	60	25.8%	1.2 - 1.3	Stable development
5	100	108	59	26.5%	1.3 - 1.4	Efficiency saturation
6	120	108	59	26.5%	> 1.4	Risk of localized failure

Analysis of the results in Table 2 reveals a distinct non-linear relationship between the pre-stress level and tunnel stability. Within the pre-stress (Pt) range of 20 kN to 60 kN, the deformation reduction rate is most significant, while the compacted arch thickness (hv) increases rapidly to establish a continuous boundary around the tunnel. However, as the pre-stress exceeds 80 kN, the displacement reduction efficiency improves by only 1-2%, indicating a saturation state of the reinforcing arch. These findings confirm that a pre-stress level of 60 kN represents the optimal intersection of technical performance and economic efficiency, effectively preventing risks of anchor material failure caused by excessive stress concentration.

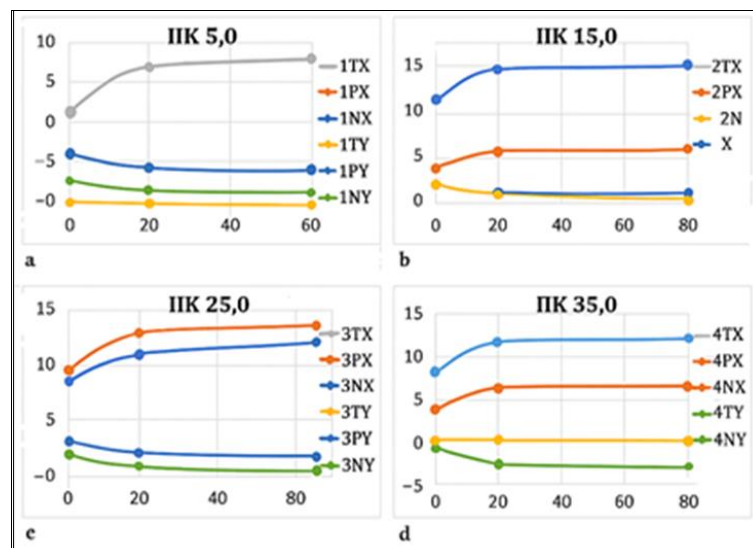
4.4. Field experimental validation

Field monitoring at the Southwest I cross-cut roadway (-230 m level) was conducted to validate the numerical simulation and assess the real development of the reinforcement arch. The recorded displacement curves show that the roadway experienced rapid convergence immediately after excavation due to stress redistribution, but deformation slowed markedly once the prestressed bolts were fully installed and tensioned to approximately 50-60 kN. After about 15-20 days, the convergence curves stabilized, confirming the transition of the surrounding rock from active deformation to a self-supporting state. This behavior corresponds closely with the FLAC3D predictions, which indicated that a prestress of around 60 kN creates a sufficiently thick compressive zone, limiting plastic

expansion and stabilizing the rock mass.

A comparison between simulation outputs and field measurements further verified the model's reliability. The numerical model predicted roof and sidewall displacements of 111 mm and 61 mm, respectively, and field monitoring produced nearly identical values (110-115 mm for the roof and 60-63 mm for the ribs). The observed rate of convergence reduction also followed the same trend as the simulation, indicating that the reinforcement arch had formed continuously around the roadway. Complementing displacement measurements, on-site pull-out tests demonstrated an average bond strength of 52.8 kN, aligning with the optimal prestressing range derived from the simulation. This confirms that the bolt-grout-rock interface could effectively transfer prestress without slippage, ensuring that the reinforcement mechanism functioned as theorized.

Long-term observation showed no cracking or deterioration in the shotcrete layer, nor any loss of prestress or signs of localized rock failure, confirming that the reinforcement arch remained stable throughout the monitoring period. The consistency among numerical predictions, deformation measurements, and pull-out test results provides strong evidence that a prestressing force of about 60 kN is both technically effective and structurally safe. Overall, the field validation confirms that the simulation accurately reflects real ground behavior and that the prestressed bolting system successfully establishes a stable reinforcement arch within the geological conditions of the Mao Khe mine.



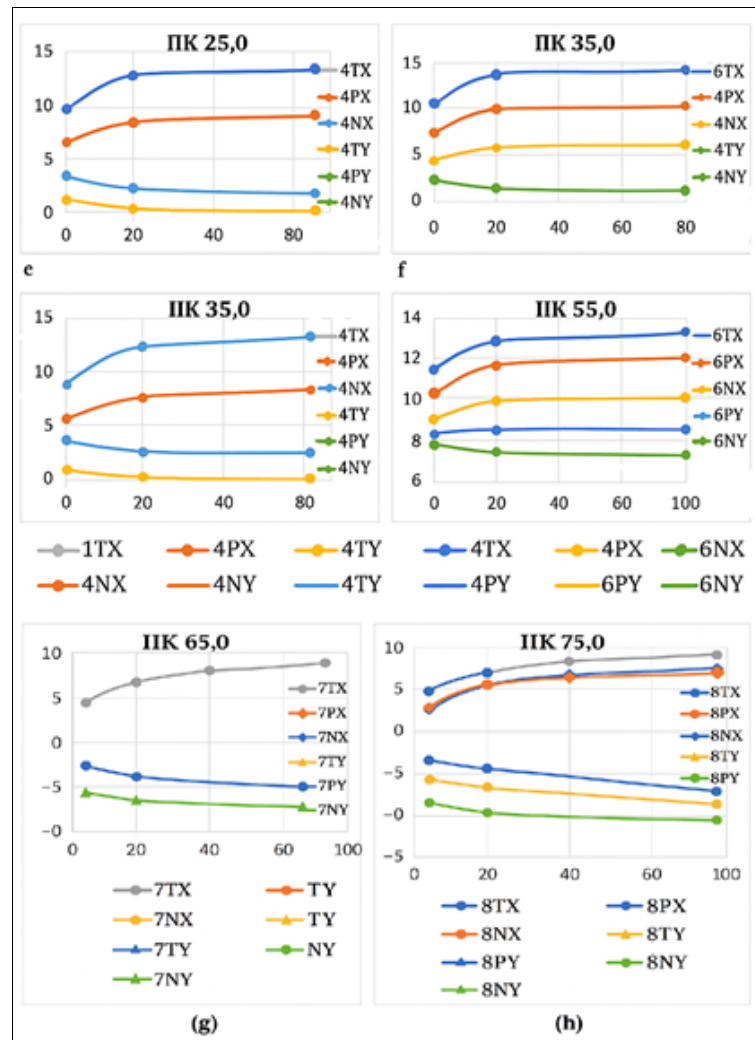


Fig 8: Displacement charts of measurement points on each cross-section

5. Conclusion

This research successfully establishes a quantitative relationship between bolt prestress and the self-supporting capacity of the surrounding rock mass, confirming that prestress is the decisive factor in mobilizing the rock's inherent strength. The methodology, validated by in-situ monitoring and pull-out tests (52.8\$ kN), reveals a non-linear efficiency saturation point: while increasing prestress up to 60 kN rapidly enhances the thickness of the compacted arch, exceeding 100 kN yields marginal stability gains and risks localized material failure at the bolt threads. Future research should extend these findings to investigate the long-term durability of the reinforcement arch under the influence of mine humidity and the dynamic stress induced by adjacent mining activities. Establishing these time-dependent variables will be crucial for refining the lifespan of support systems in increasingly hazardous deep-mining environments.

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