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ANALYSIS OF BEHAVIOUR OF THE STEEL ARCH SUPPORT IN THE GEOLOGICAL AND MINING CONDITIONS OF THE CAM PHA COAL BASIN, VIETNAM

In recent years, the Vietnamese coal mining industry has observed a dynamic increase in both its production and efficiency. In Vietnam, the most precious type of coal is anthracite, which is found in the Quang Ninh province. Industrial anthracite deposits are estimated to be over 2 billion Mg. At present, coal deposits are extracted mostly by the underground method. Coal production is gradually increasing in the underground mines in the Quang Ninh area and it is expected to constitute about 75% of the country's total coal production in 2030. This involves an increase in the number and length of underground workings.

Cam Pha is the largest coal basin of Vietnam, located in the Quang Ninh province. So far, the yearly length of underground workings driven in underground mines in the Cam Pha basin is roughly 90÷150 km. About 84 % of these underground workings are supported by the steel arch support made of SWP profile. A similar situation can be observed in Russia, Ukraine, China, India and Turkey. In addition, the average length of repaired underground workings in the Cam Pha basin constitutes approximately 30% of the total length driven . The main cause was reported is loss of underground workings stability. This requires significant material and labour costs as well as the cost of replacing damaged elements. Additionally, it disturbs the continuity of the mining operations.

This article presents the results of the numerical modelling of the rock mass around underground workings driven in typical geo-mining conditions for underground coal mines in the Cam Pha basin, supported by the steel arch support made of SWP and V profiles. As a result of the conducted analyses, the range of failure zone of the rock mass around underground workings and the distribution of reduced stress in the steel arch support elements were determined. The effort states of the steel arch support made of SWP22 profile and V21 profile were compared. The simulations considered different inclinations angle of coal seam, following the structure of the rock mass in the Cam Pha basin. The analysis was carried out using the based-finite difference method code, FLAC2D. Based on the obtained results, actions for improving the stability of underground workings driven in the underground mines of the Cam Pha basin were proposed.

Keywords: Steel arch support, profiles of steel arch support, numerical analysis, Vietnamese coal mining industry

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1. Introduction

In recent years, the Vietnamese coal mining industry has observed a dynamic increase in the volume of its production and its efficiency [1-3]. In Vietnam, the most precious type of coal is anthracite, which is found in the Quang Ning province. Industrial anthracite deposits are estimated to be over 2 billion Mg [4]. At present, the deposits of anthracite are extracted mostly by the underground method. Coal production in the underground mines of the Quang Ninh area is gradually increasing and is predicted to reach to approximately 75% of the country's total coal production in 2030 (Fig. 1) [5,6]. This involves an increase in the number and the length of driven underground workings.

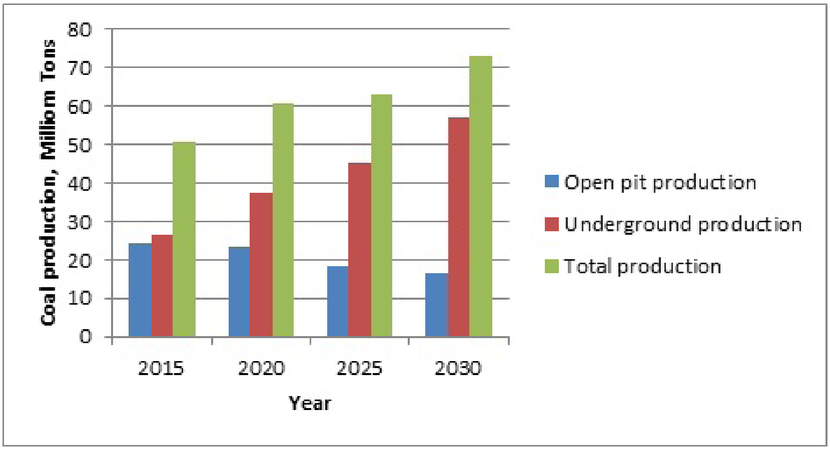


Fig. 1. Plan of hard coal production (anthracite) in Vietnam by 2030 with the distribution of open pit production and underground production [4]

Cam Pha is the largest coal basin in Vietnam, located in the Quang Ninh province. Currently, the yearly length of the underground workings driven in the underground mines of the Cam Pha basin is approximately 90÷150 km. Yielding steel arch supports made mainly of SWP profiles are applied in order to support 84% of total underground workings [7-10]. Last decades, in Germany 65% of roadways were supported by steel arch support made of U profiles [11,12]. In Poland, the majority of roadways are support by ŁP yielding steel arch support made of V profiles [13,14]. In Russia, Ukraine, China, India and Turkey, the situation is similar [15-18]. In 2013÷2017, the average yearly length of rebuilt underground workings in Cam Pha underground mines was 23.5÷42 km, which was approximately 30% of the total length driven underground workings. The main reason of failure of underground workings was loss of stability [19-21], as shown in Figure 2. This results in significant material and labour costs associated with replacing the damaged elements, and it also disturbs the continuity of mining operations. Due to this fact, the aim of this paper is to identify the causes that lead the underground workings to loss of their stability and to assess if it is possible to apply other types of steel arch support, which are capable for the geo-mining conditions of the Cam Pha coal basin. This article presents the geological and mining conditions of the Cam Pha coal basin. Based on these conditions, numerical calculations for selected profiles of the steel arch support (SWP and V) were conducted. In the analyses, the values of reduced stress and the range of failure zone for the steel arch support made of selected profiles were compared.

Fig. 2. Loss of stability of underground workings in the Cam Pha coal basin

2. Characteristics of geo-mining conditions in the Cam Pha coal basin

2.1. Location

The Cam Pha basin is the biggest coal basin in Vietnam. Its hard coal deposits, mostly of anthracite, are estimated close to 1.5 billion Mg. In this area, six large underground mines operate, including: Khe Cham, Mong Duong, Thong Nhat, Duong Huy, Ha Long and Quang Hanh (Fig. 3). In a period of 2013÷2017, the yearly hard coal production in the Cam Pha region was in a range from 8.5to 10.5 million Mg [4,19,22].

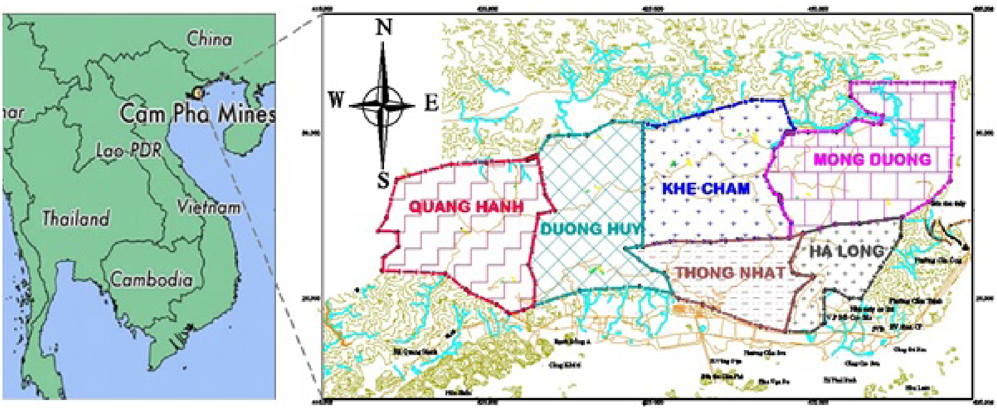


Fig. 3. Location of underground mines in the Cam Pha coal basin, Quang Ninh province [4]

2.2. Depth of the underground exploitation

The underground coal mines of the Cam Pha basin are, at present, exploited at depths of approximately 200÷500 m.b.g.l. Depending on the terrain, shape and tectonics of the deposit, the level of exploitation and the actual depth of exploitation can differ significantly [19,22]. Table 1 summarises the depth of exploitation at some underground mines in the Cam Pha basin.

TABLE 1

Depth of the underground exploitation in the Cam Pha basin

Mine	Coal seam	Depth from the surface (m)
Duong Huy	V3÷V16	200÷250
Thong Nhat	V1÷V6	300÷350
Quang Hanh	V3÷V17	250÷300
Mong Duong	V.I, II, H, G, K, V6, V7, V8, V9, V10	350÷400
Khe Cham	V11, V12, V13-1, V13-2, V14-2, V14-4, V14-5, V15 and V16	445÷515

2.3. Geological structure

The geological conditions in the Cam Pha region are unfavourable for conducting the underground operation, following:

- the rock mass consists of strong/hard rocks such as: conglomerate, sandstone, mudstone, claystone and coal (Fig. 4, Table 2). The average values of the compressive strength of the rocks are between 30 MPa and 120 MPa [23]. The significant inclination angle of the rock layers poses a major challenge to underground exploitation.
- coal seams with a thickness greater than 3.5 m dominates close to 60% of the total coal seams in region; coal seams with inclination of 15° to 35° are over 60% of the total coal seams, as presented in Figure 5 [23],
- there are also a lot of faults and folds in the Cam Pha basin (Fig. 6).

TABLE 2

Mechanical parameters of intact rocks in the Cam Pha basin [23]

Type of rock	Compressive strength, R_c (MPa)	Tensile strength, R_t (MPa)	Young's modulus, E (GPa)	Poisson's ratio, υ	Cohesion, c (MPa)	Friction angle, φ (o)	Density, γ (kg/m^3)
Conglomerate, coarse-grained sandstone	102.6	7.8	16.8	0.25	18.7	33	2580
Sandstone	92.0	10.5	18.7	0.25	30.2	30	2620
Mudstone	46.7	5.5	8.6	0.25	12.2	29	2600
Claystone	20.0	1.8	3.7	0.25	4.8	32	2640
Coal	15.0	1.2	3.4	0.25	2.1	27	2460

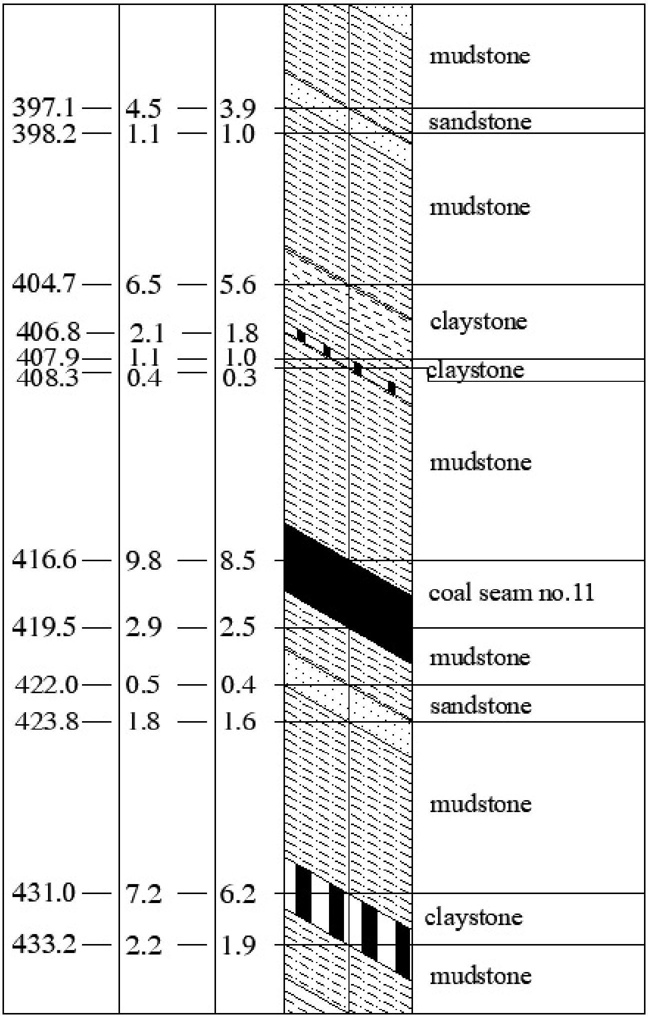


Fig. 4. An example of lithological profile at the Khe Cham underground coal mine, the Cam Pha basin [23]

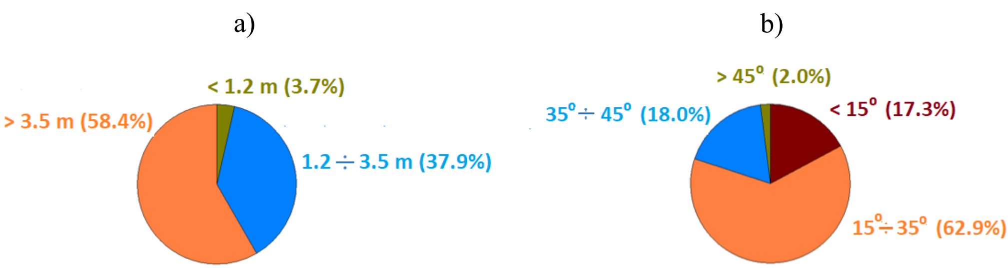


Fig. 5. Characteristics of coal seams: a) thickness, b) inclination angle [23]

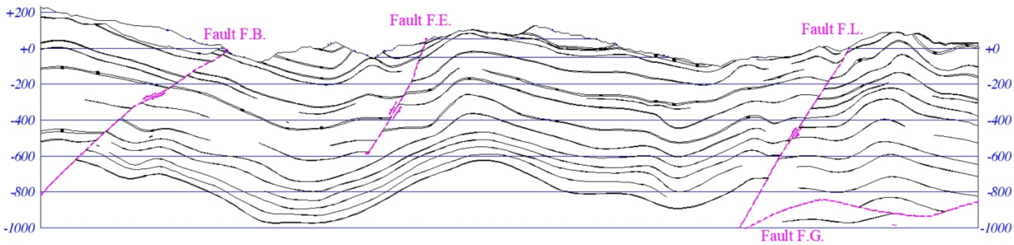


Fig. 6. Fragment of the lithological cross-section in the Cam Pha basin
(faults – pink; coal seams – black) [23]

2.4. Tectonic disturbances

According to available researches, conducted by the Institute of Mining Science and Technology (Vietnam) [23], in the Cam Pha basin there are numerous faults (Table 3).

TABLE 3

General characteristics of the main faults in the Cam Pha basin [23]

Name of fault	Type of fault	Fault zone [m]	Heave [m]	Dip /Dip direction [^{o}]
F.A	Reverse	No data	No data	50-65/175
F.L	Reverse	30-50	No data	50-70/190-270
F.3	Reverse	10-15	100-150	75-80/170
F.I	Reverse	No data	No data	55-60/200
F.G	Reverse	10-25	100-140	70-80/180
F.B	Normal	No data	200-400	60-65/175
F.BL	Normal	5-15	ok. 100	50-60/200
F.E	Normal	15-30	ok. 150	50/210
F.BH	Normal	No data	200-400	60-65/200

2.5. Hydrogeology

The hydrogeological conditions in the Cam Pha basin can be characterised as follows [23]:

Surface water from open pit mines, rivers and streams, that supplied by rainfall (average rainfall of 1,700÷2,900 mm/year, and in the rainy season even up to 350 mm/day). Surface water is the main source which provides water to the aquifers.

Underground waters occur in the Quaternary layers, Carboniferous layers and in the zones of tectonic disturbances.

– **Water in Quaternary layers** occurs only in the rainy season. The water occurs in the form of either aquifers or aquitards, depending on the lithological and structural conditions. The measurements show that the flow rate is 0.001÷1.51 L/second, and the permeability ratio is 1.98÷7.33 m/day.
– **Water in Carboniferous layers** occurs as aquitards in hydraulic contact with the Quaternary aquifer. The permeability ratio is, on average, approximately 0.015÷ 0.04 m/day.
– **Water in faults.** Its occurrence is approximately 40 times lower than in the Carboniferous layers. The permeability ratio is, on average, 0.001÷0.005 m/day.

2.6. Brief characteristics of underground workings in the Cam Pha coal basin

At present, in Vietnamese underground coal mines, underground workings are driven mainly using explosive material. The average advance rate of the underground working face is 60÷120 m/month. Most of the underground workings are supported by the yielding steel arch support made of SWP profiles (SWP17, SWP22, SWP27 and SWP33) (Fig. 7), rolled from St5 steel. Both the profiles and steel types are performed based on Russian standards [24], and the main producer is Thai Nguyen Steel Mill [22,25]

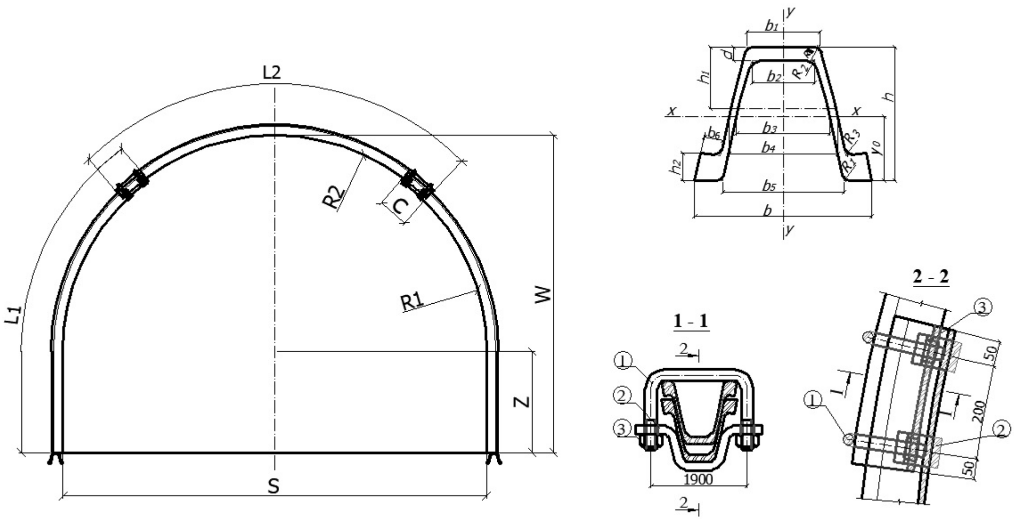


Fig. 7. Typical steel arch support with SWP profile applied in underground mines in Vietnam [24]

3. Numerical analysis

To observe behaviour of the rock mass surrounding underground workings, the stress state of the steel arch support and the interaction between the steel arch support and the rock mass, numerical analysis was conducted. FLAC2D software [26], based on the algorithms of the finite difference method, was applied.

3.1. Modelling of steel arch support

Numerical simulations were conducted for an underground working supported by the steel arch support made of SWP profile and V profile. Their cross-section parameters are presented in Table 4.

Figure 8 presents outlines of the analysed profiles.

TABLE 4

Cross-section parameters of the analysed profiles

Profile	A	H	B	e	I_x	I_y	W_X	W_Y
	cm^2	mm	mm	mm	cm^4	cm^4	cm^3	cm^3
SWP22	28.51	100	144	58.1	436.6	596.7	75.1	82.6
V21	26.72	108	125	51.5	334.0	392.4	59.1	62.7

A – cross-sectional area of a profile; H – cross-sectional height of a profile; B – cross-sectional width of a profile; e – location of neutral axis during elastic bending; I – main central moment of the inertia of the cross-section; W – cross-section modulus index.

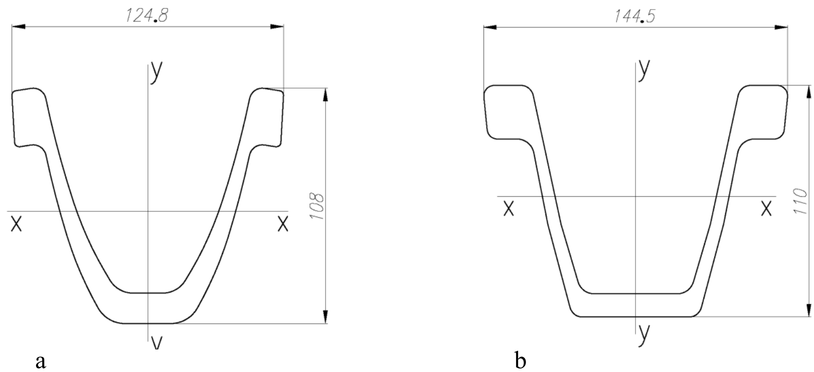


Fig. 8. Cross-section dimensions of a profile: a) V21, b) SWP22

The results obtained with the numerical model were used to calculate the reduced stress following the Huber-von Mises-Hencky hypothesis with the equation [27]:

$$\sigma_{red} = \sqrt{\left(\frac{M_g}{W_x} + \frac{N}{A}\right)^2 + 3 \cdot \left(\frac{T}{A}\right)^2} \tag{1}$$

where: M_g – bending moment, W_x – cross-section modulus index, N – axial force, A – cross-sectional area, T – transverse force.

The obtained values of the reduced stress were referred to the acceptable values, specified as the maximum value of stress which can be carried by SWP profiles and V profiles made of the selected steels. The performance of the plasticised profiles was also considered. The parameter, considering mechanical properties of steel and the shape of a profile cross-section, can be determined with the following dependence [28]:

$$\sigma_{per} = \frac{R_e \cdot (m+n)}{\gamma_s} \tag{2}$$

$$m = \frac{W_{pl}}{W_x} \tag{3}$$

$$n = \frac{R_m - R_e}{R_e} \tag{4}$$

$$W_{pl} = |S_c| + |S_r| \tag{5}$$

where: R_e – yield point, m – shape factor, n – material plasticity coefficient, R_m – tensile strength, γ_s – factor of safety according to PN-90/B-03200 [29], W_x – section modulus, W_{pl} – plastic modulus, S_c – first moment of compression section, S_r – first moment of tension section.

The cross-section and material parameters of SWP22 profiles and V21 profiles made of the steels (St5, 25G2, S480W and S550W), calculated in the aforementioned way, are collected in Table 5. The parameters mentioned in standards PN-H-93441-3 [30] and GOST [24], as well as the minimum values of and for a given grade of steel were also considered.

TABLE 5

Cross-section parameters of the analysed profiles

Profile	**Material (type of steel)**	**Plastic modulus, W_{plX}**	**Shape factor, m**	**Material plasticity coefficient, n**	**Factor of safety, γ_s**	**Permissible stress, σ_{per}**
		cm^3	—	—	—	**MPa**
SWP22	St5	102.0	1.357	0.6212	1.15	498.8
V21	25G2	85.7	1.450	0.6176	1.15	611.3
	S480W			0.3542	1.25	692.8
	S550W			0.3273	1.25	782.0

To compare the maximum values of reduced stress with the values of permissible stress, ratio k was determined as following:

$$k = \frac{\sigma_{red}}{\sigma_{per}} \tag{6}$$

3.2. Model description

Rock mass is assumed to be homogeneous. Based on the results of laboratory tests given in Table 2, the weighted average values of mechanical parameters adopted for numerical modelling are presented in Table 6. The numerical calculation considered an underground working driven in 2.5- and 5.0-metre-thick coal seams. Additionally, different values of inclination angle of coal seam were assumed as follows: 0, 15, 30, 45°.

TABLE 6

The weighted average values of the mechanical parameters of intact rocks in the Cam Pha basin

Type of rocks	**Density, γ (kg/m^3)**	**Young's modulus, E (GPa)**	**Poisson's ratio, υ**	**Friction angle, φ (°)**	**Cohesion, c (MPa)**	**Tensile strength, R_t (MPa)**
Roof rocks	2600	8.6	0.25	32	5.8	3.1
Coal	2460	3.4	0.25	27	2.1	1.2
Floor rocks	2600	8.6	0.25	32	5.8	3.1

For simplicity, it was assumed that the strength parameters ought to be reduced to 25% and the deformation parameters to 50% for numerical calculations [31] (Table 7)

TABLE 7

Reduced mechanical parameters of rocks for numerical calculations

Type of rocks	Density, γ (kg/m^3)	Young's modulus, E (GPa)	Poisson's ratio, υ	Friction angle, φ (^{o})	Cohesion, c (MPa)	Tensile strength, R_t (MPa)
Roof rocks	2600	4.3	0.25	32	1.45	0.775
Coal	2460	1.7	0.25	27	0.525	0.3
Floor rocks	2600	4.3	0.25	32	1.45	0.775

The variants of numerical calculations are presented in Table 8

TABLE 8

Summary of the variants of numerical calculations

Type of profile	Coal seam thickness, m	Inclination angle, °
SWP	2.5	0, 15, 30, 40
	5.0	0, 15, 30, 40
V	2.5	0, 15, 30, 40
	5.0	0, 15, 30, 40

In the model, following the actual geological and mining conditions in the Cam Pha basin, it was assumed that the underground working is located at the average depth of 400 m, and the average spacing between steel arches is 0.75 m. Figure 9 shows the dimensions of a 2D simplified numerical model. The numerical model was divided into approximately 75,000 elements.

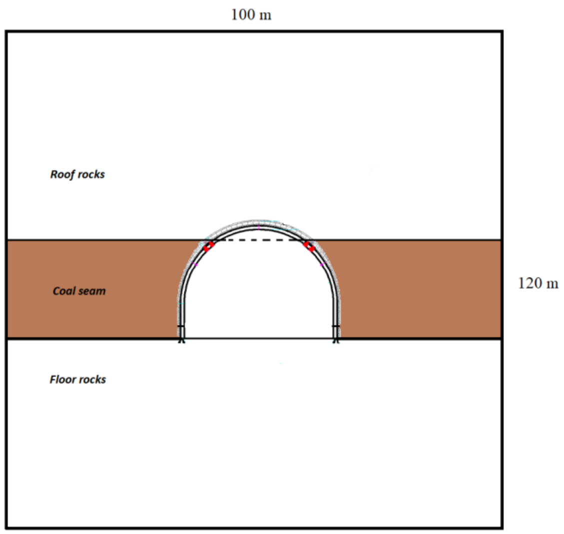


Fig. 9. Geometry of the model and location of rock layers (*no scale*)

Displacement conditions were assumed on the bottom and top edge as well as both sides. Hypothetically, the original horizontal stress equals the original vertical stress.

The steel arch support was simulated in FLAC2D using a beam profile. Mechanical parameters of the beam element were adopted: mass density is 8000 kg/m3; Poisson's ratio is 0.25; and Young's modulus is 2.0 e11 Pa.

3.3. Results analysis and comparison

As results of the calculations, the distribution of internal forces in the elements of the steel arch support – and the maps of plasticity indicator were used for the analysis. Due to the large number of obtained results, only a few graphs for a certain variant of calculations are presented.

The results of numerical calculations are presented as a graph of bending moments, shear forces and axial (longitudinal) forces (Figs 10-12).

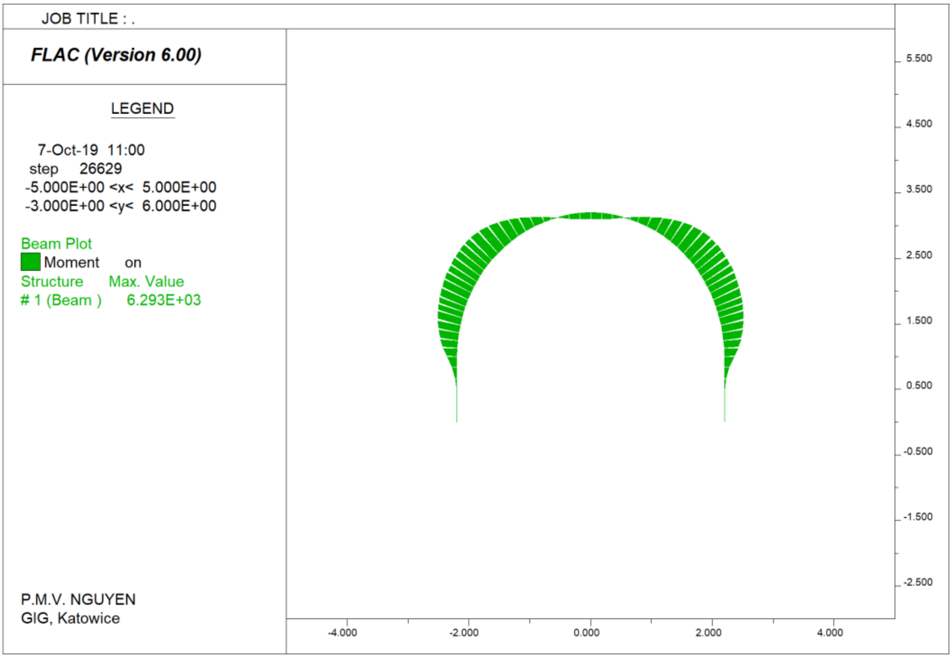


Fig. 10. Graph of bending moments in the elements of steel arch made of SWP22 profile

The calculated values of reduced stress and coefficient *k* for steel arch support made of V21 profile and SWP22 profile are presented in Table 9.

The results from Table 8 are presented as a graph in Figure 13.

Additionally, Table 9 presents maps of plasticity indicators determining the range of the shear failure zone (marked as red '*') and the tensile failure zone (marked as pink 'o') around the underground workings.

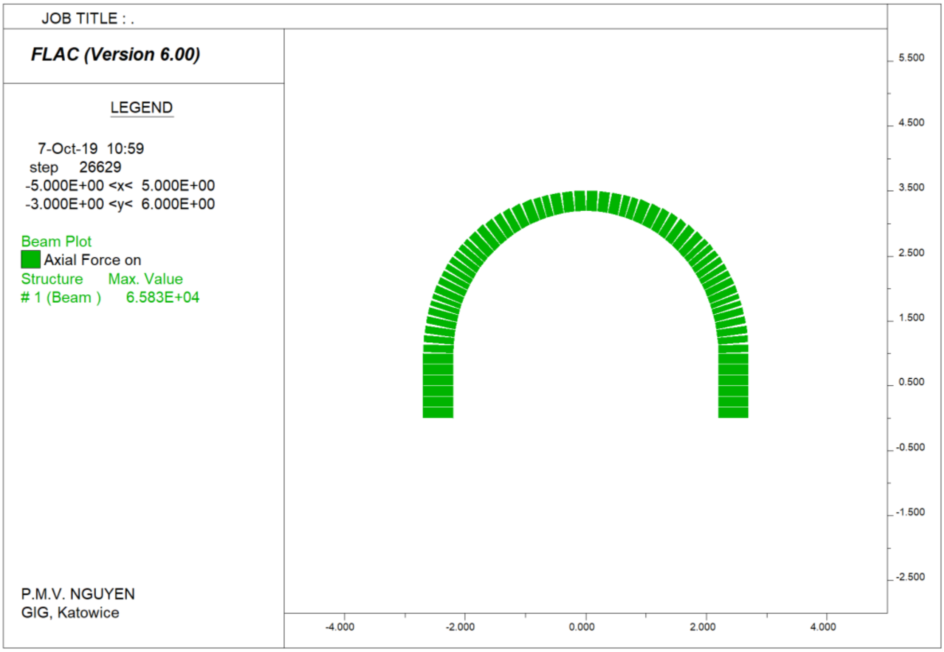


Fig. 11. Graph of axial forces in the elements of steel arch made of SWP22 profile

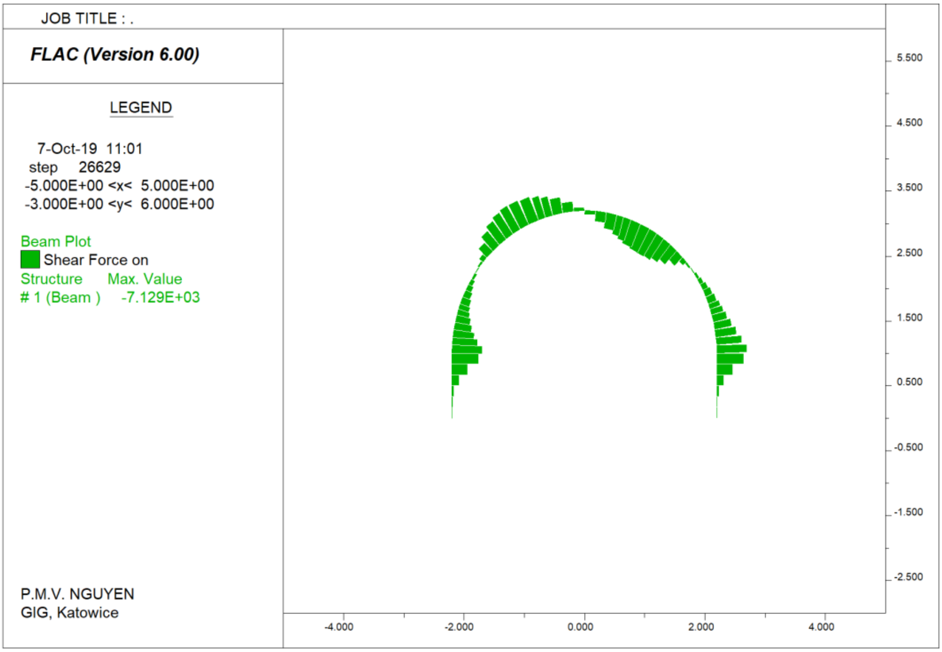


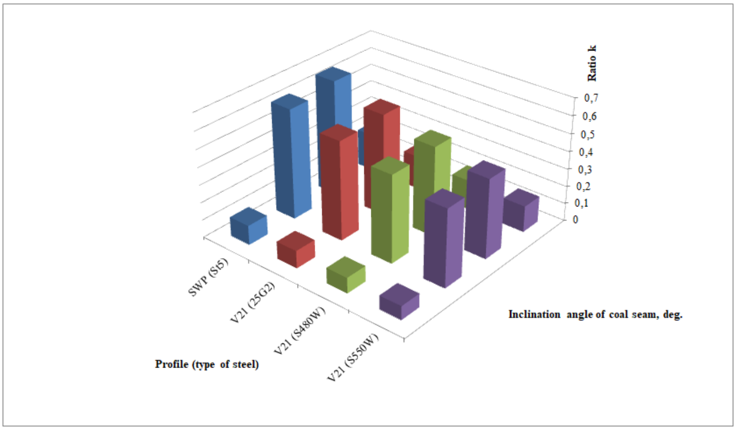
Fig. 12. Graph of shear forces in the elements of steel arch made of SWP22 profile

TABLE 9

Comparison of the maximum values of reduced stress in the steel arch support made of profiles V21 and SWP22 related to the permissible values

Seam thickness, m	Inclination angle, °	Maximum value of reduced stress, σ_{red}, MPa		Ratio k			
		SWP22	V21	SWP22 (St5)	V21 (25G2)	V21 (S480W)	V21 (S550W)
2.5	0	106	117	0.212	0.191	0.168	0.149
	15	330	353	0.661	0.577	0.509	0.451
	30	313	344	0.627	0.562	0.496	0.439
	45	55	61	0.110	0.099	0.088	0.078
5.0	0	121	135	0.242	0.220	0.194	0.172
	15	357	387	0.715	0.633	0.558	0.494
	30	346	371	0.693	0.606	0.535	0.474
	45	165	183	0.330	0.299	0.264	0.234

a



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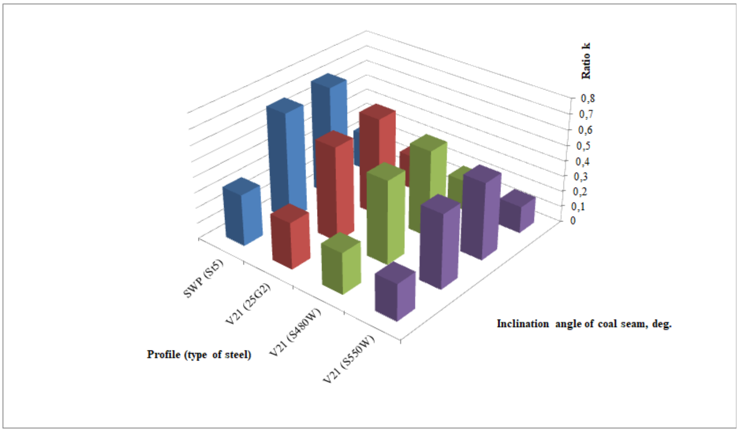

Fig. 13. Coefficient k: a) 2.5-metre-thick seam, b) 5.0-metre-thick seam

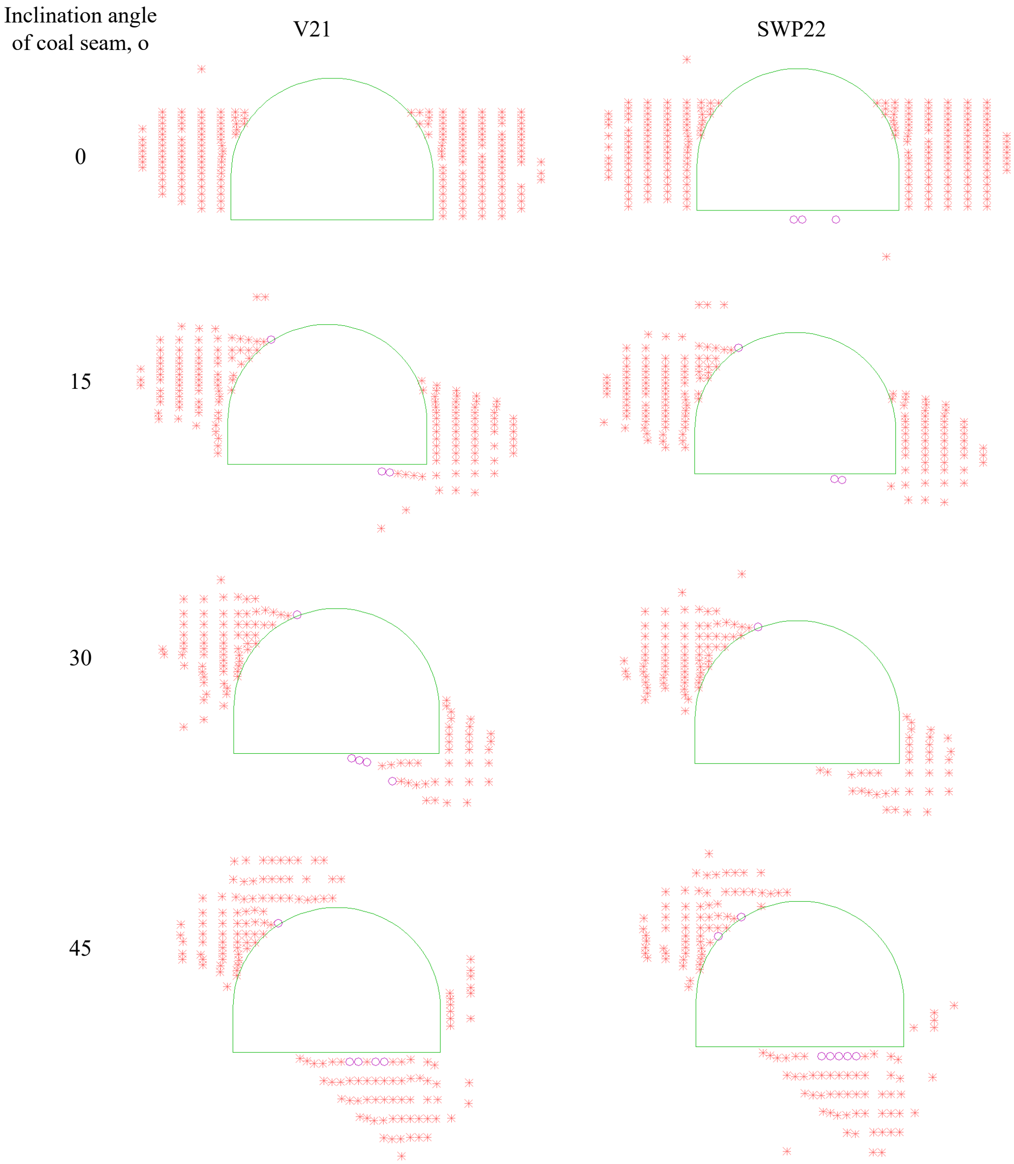

Fig. 14. Comparison of the range of failure zone around the underground workings supported by the steel arch made of V21 profile and SWP22 profile for a 2.5-metre-thick coal seam

4. Discussion

The maximum values of reduced stress in the steel arch support made of V21 profiles are slightly higher than the values of reduced stress in the steel arch support made of SWP22 profile (Table 9). This means that the steel arch made of SWP profiles with the same type of steel as V profiles is capable of carrying slightly higher loads from rock mass in the same conditions. It ought to be noted that the steel arch made of SWP22 profile has slightly greater weight than the steel arch of V21 profile. Additionally, SWP22 profile has slightly higher cross-section parameters (Table 4). It may be concluded that behaviour of the steel arch support made of both profiles (SWP and V) is similar. However, considering the material and cross-section parameters of both profiles in the plasticity state, the arch made of V profile with steel types of 25G2, S480W and S550W, deal better with the stress state than the arch made of SWP222 profiles with the St5 steel, it is indicated by the values of coefficient *k*, collected in Table 9 and in Figure 13. This also shows that arch made of V profiles have higher load-bearing parameters. This was also confirmed by Rotkegel and Grodzicki [32] and Hałat [33]

In both the steel arches made of SWP22 profile and of V21 profile, the value of stress increases together with the rising inclination angle of a coal seam from 0° to 30°. For the inclination angle of 45°, the value of reduced stress decreases by half from the value of reduced stress at a 0° inclination angle of a coal seam. For greater values of the inclination angle (≥45°), part of the gravitational load from the rock mass transforms into shear force, which is probably greater than the shear strength, thus, the steel arch support carries lower load-bearing than in the case of the inclination angle of 0° (Table 9).

The range of failure zone around the underground workings supported by the steel arches made of SWP22 profile and V21 profile are similar (Fig. 14). For both profiles (SWP22 and V21), the range of failure zone increases together with an increase of the inclination angle (from 0° to 30°) and then decreases at the inclination angle of 45°. This confirms the tendencies of changes in the values of reduced stress in the steel arches shown in Table 9.

5. Conclusions

Based on the conducted numerical calculations concerning the interaction between the rock mass and the steel arch support made of SWP22 profile and V21 profile and considering the actual geological and mining conditions in the Cam Pha basin, it is possible to formulate the following conclusions and recommendations:

- in the geological and mining conditions of the Cam Pha basin, behaviour of a steel arch support made of SWP profile is similar to behaviour of a steel arch support made of V profile. The mechanical parameters of the steel used for SWP profiles are lower than the parameters of the steels used for V profiles. The low parameters of steels for the steel arch support applied in the underground mines in the Cam Pha basin may be a reason why it is difficult to maintain stability of underground workings. Difficulties may also result from specific characteristics of the driving method (explosive material) and the method of assembling the steel arch support.
- it seems that the capability of the steel arch support made of V profile with higher quality of steel may be suitable for the geological and mining conditions of the Cam Pha coal basin.
- it is appropriate to conduct comparative standing tests of steel arches made of SWP profile and V profile to determine their actual load-bearing capacity
- it is necessary to apply different steel types with higher quality (e.g. S480W, S550W) to perform the steel arch support for underground working at coal mines in the Cam Pha basin.

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