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Applying Artificial Pillar to Replace the Coal Pillar Protecting Roadway to Increase Production Efficiency and Sustainable Development in the Vietnamese Coal Industry

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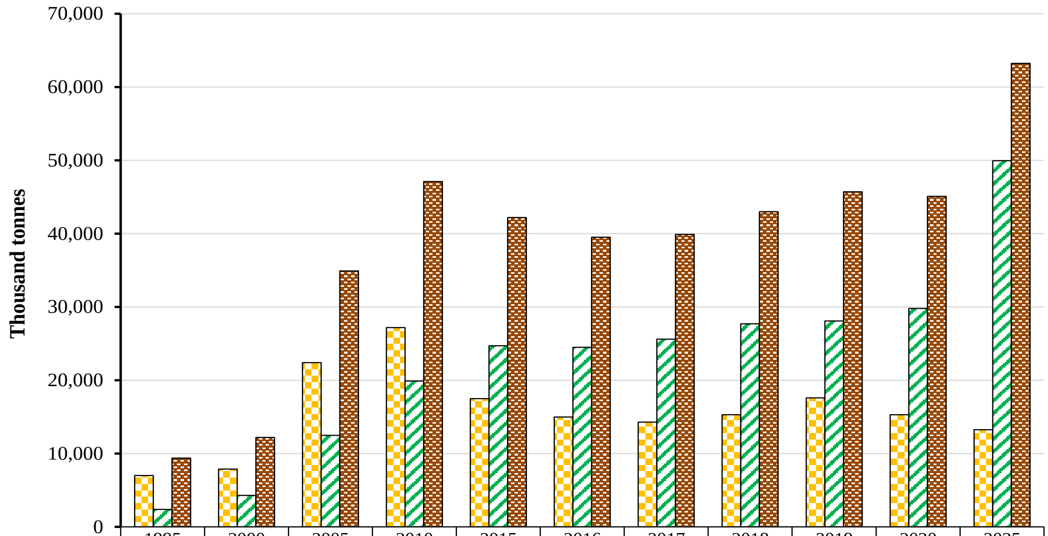
Abstract. Vietnam's domestic coal production is growing fast and is expected to reach 68.9 million tons in 2030, nearly 1.5 times higher than today. Open-pit mines will gradually reduce production and close, and underground mining coal output will increase progressively year by year and take a leading role. Besides the investment in new mines to achieve these goals, it is necessary to maximize the coal reserve exploited annually of existing underground mine projects, which its coal reserve in pillars protecting roadways currently accounts for 12−15%. The further exploitation of this coal reserve will decrease the costs of preparation of underground mines and granting mining rights and depreciation of infrastructure assets. Moreover, it will help reduce the loss of non-renewable resources and contributing to the sustainable development of Vietnam's coal industry.

Keywords: coal pillar protecting roadways; coal loss; artificial pillar; underground mine

1. Introduction

In the last twenty-five years, Vietnam's total annual coal production increased rapidly from 9.4 million tonnes in 1995 to 34.9 million tonnes in 2005 and to 45.1 million tonnes in 2020 (which grew about 4.8 times). According to the Master Plan of Coal Industry Development in Vietnam by 2020, outlook to 2030 (Decision No.403/QD-TTg dated March 14, 2016), the domestic coal production will increase to 63.22 million tonnes in 2025, in which the open-pit's output will decrease from 15.3 million tonnes in 2020 to 13.27 million tonnes in 2025. However, coal production of underground mines is growing faster, from 29.8 million tonnes in 2020 to 49.94 million tonnes in 2025, an increase of 1.7 times compared to the present and accounted for nearly 80% of the national coal output.

Figure 1 illustrates details of the Vietnamese coal production during 1995–2020 and outlook to 2025.



	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2025
Open-pit	7,000	7,900	22,400	27,200	17,500	15,000	14,300	15,300	17,600	15,300	13,273
Underground	2,400	4,300	12,500	19,900	24,699	24,500	25,600	27,700	28,100	29,800	49,942
Total	9,400	12,200	34,900	47,100	42,199	39,500	39,900	43,000	45,700	45,100	63,215

Fig. 1. Vietnamese coal production during1995–2020, outlook to 2025 [1].

To achieve this goal, along with opening new mines, the maximum exploitation of coal reserves in underground mines is also an important issue. The most feasible way is to exploit coal reserves in pillars protecting roadways, which account for 12–15% of total coal reserves of mining projects. There are available coal reserves that are considered inevitable losses due to a lack of appropriate mining technology. Suppose coal reserves in pillars are exploited, in addition to reducing the loss of non-renewable resources. In that case, it will bring a wide range of economic efficiency for mining companies, such as reducing the cost of preparing excavation, depreciation costs of opening mines, infrastructure, cost of granting mineral mining rights. Experience in some countries with mineral development, such as Russia, Poland, and China, showed an appropriate and feasible direction to increase the coal industry's production efficiency and sustainable development.

2. Current situation of underground mining cost of Vietnam National Coal - Mineral Industries Holding Corporation Limited

In Vietnam, coal is exploited by Vietnam National Coal-Mineral Industries Holding Corporation Limited (VINACOMIN), Dong Bac Corporation (a military-run economic unit under the Ministry of National Defense), and a few private companies. VINACOMIN is the leading producer and supplier, with an annual output accounting for about 85% of the national coal output. In this paper, the authors research the technology of production of underground coal mines of VINACOMIN.

Currently, underground coal companies/mines of VINACOMIN are mainly located in Quang Ninh province (13 coal mines), with a length of nearly 100 km from Dong Trieu district (Mao Khe and Uong Bi coal mines) to Cam Pha city (Khe Cham coal mine and Mong Duong coal mine). The majority of exploited coal from underground mines (raw coal) is delivered to a transportation company for central processing plants to be ready for consumption. Therefore, in underground coal mines of VINACOMIN, the cost of coal production will be mainly direct production costs and a small ratio of consumption and management cost. From the production and business plans of some underground coal mines in Quang Ninh province, the production costs depend on production conditions (geological conditions, mining technologies applied in the production lines, etc.) and volume of infrastructure investment, ranged from 49.3 Euros to 52.7 Euros per ton in 2020. It is worth noting that direct costs reach 89.6–91.4%, consumption, and management costs are only 8.55% or 10.48%. Details of the total cost of coal mining are in Table 1.

Tab. 1. The total cost of coal production by production stages in underground coal mines of VINACOMIN in 2020 [2].

No	Cost		Value (VND per ton)			Ratio compared to I
			Smallest	Largest	Medium	
I	**Direct production costs**		**1,231,023**	**1,297,761**	**1,275,746**	**100%**
1	Cost of driving prepared roadways		146,338	293,816	204,539	16.03%
2	Cost of mining coal in longwall		257,992	285,105	270,145	21.18%
3	Cost of infrastructure depreciation		37,360	118,613	81,573	6.39%
4	Cost for mining rights		26,120	26,120	26,120	2.05%
5	Others		671,676	729,257	693,370	54.35%
II	**Consumption cost**		**2,141**	**2,622**	**2,483**	-
III	**Cost for enterprise management and other costs**		**118,251**	**149,139**	**133,970**	-
IV	**Total cost of coal production by stages (I + II + III)**		**1,355,078**	**1,449,477**	**1,412,199**	-
V	**Proportion (%)**	**I/IV**	**89.53**	**91.42**	**90.35**	-
		II/IV	**0.16**	**0.19**	**0.18**	-
		III/IV	**8.39**	**10.29**	**9.47**	-

The results in Table 1 show that VINACOMIN is maintaining its advantage of mass production. Costs account for a large proportion, including the cost of driving prepared roadways (204,539 VND per ton, accounting for 16.03% of production costs), the cost of mining coal in longwall (270,145 VND per ton, 21.18%), depreciation (81,573 VND per ton, 6.39%), and mining rights (26,120 VND per ton, 2.05%). These costs accumulate 582,377 VND per ton, account for 45.65% of direct production costs (see Figure 2). Thus, it is necessary to research and apply new technologies to exploit coal reserves in pillars protecting prepared roadways in underground coal mines.

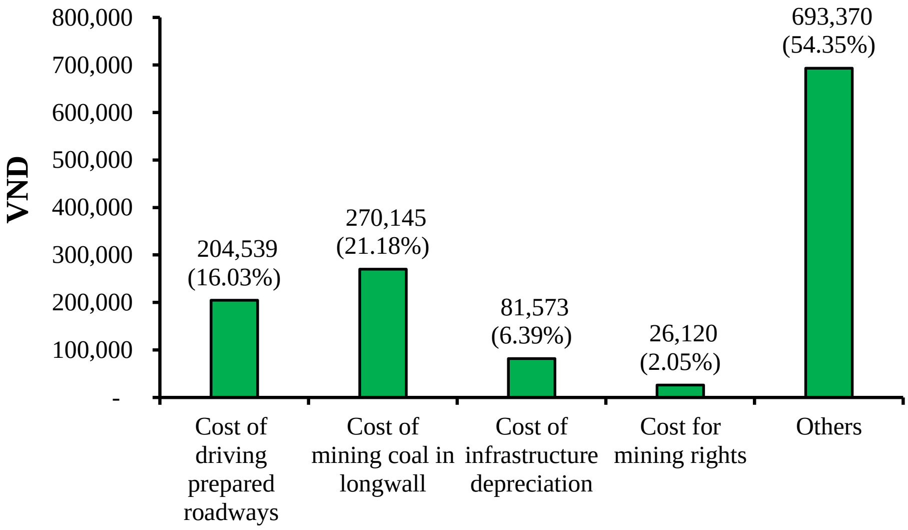


Fig. 2. Structure of direct production costs.

3. Evaluate the potential of using artificial pillar to replace the coal pillar protecting roadway in underground coal mines in Quang Ninh province

3.1 Experience in using artificial pillars to replace the coal pillar protecting roadway in the world

Underground mining in Quang Ninh is mainly longwall, mining along the strike of the coal seams. The preparation method can be generalized as 121 (Figure 3a). Each (1) longwall will have two (2) roadways (ventilation roadway, transport roadway) and one (1) coal pillar to protect from 15–18m to maintain the transportation roadway as a ventilation roadway for the next longwall. The length of longwall in underground mines of VINACOMIN is from 100–150m, an average of 120m. The rate of coal loss due to technical requirements of protection pillars accounts for 12–15% of the total coal reserves in the longwall mining area. Hence, not only the rate of coal loss but also production costs increase.

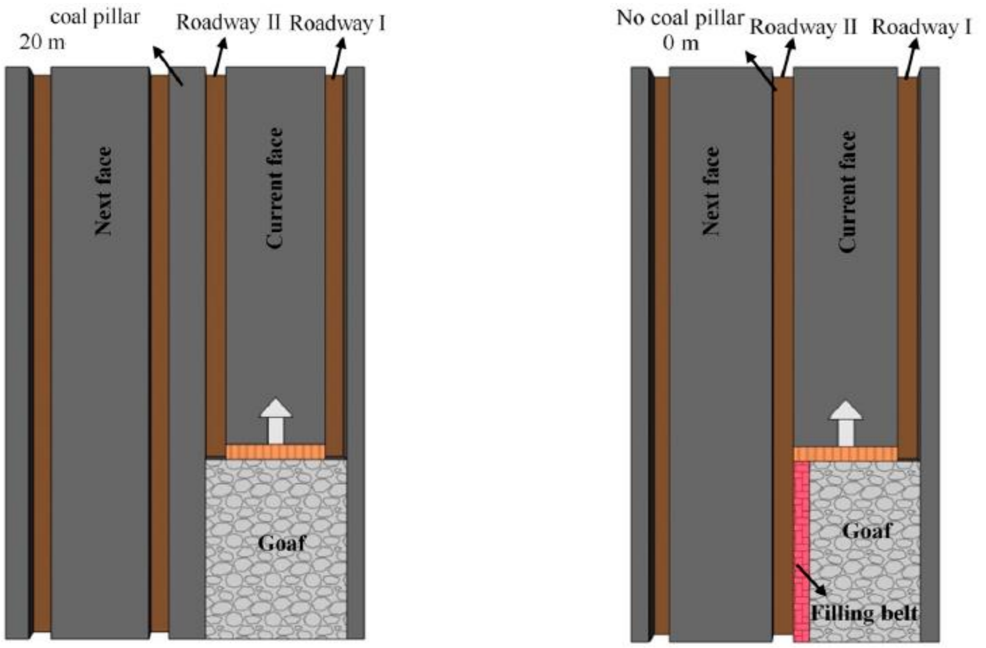
Countries such as Russia, China, Poland [3, 4, 5, 6] have successfully applied artificial pillars to replace coal pillars protecting preparation roadways to overcome the rise of coal loss and production costs. Accordingly, to simultaneously extract coal in the protection pillar and maintain the transport roadway as a ventilation roadway of the next longwall, the protected coal pillar will be replaced by artificial pillars. The materials used to construct the pillars can be clustered columns, wooden/metal cribs, stone cribs, brick/rock blocks, or chemical materials. With diagram 121, each (1) longwall only has one (1) prepared road and one (1) artificial pillar to replace the coal pillar (the preparation and exploitation scheme of this type is generalized to 111 in Figure 3b). Thus, compared to diagram 121, the type 111 scheme has allowed reducing the rate of coal loss in the protection pillar and the driving cost of prepared roadway (reduction 01 roadway). Meanwhile, the ability to isolate the roadway from the mining area to reduce the impacts of water, toxic gas and prevent endogenous fire is well-performed. It is because the artificial pillar is constructed continuously on the side of the roadway.

Recently, coal mining companies in China [7, 8] have applied the scheme of preparing roadways for longwalls to exploit coal without protection pillars (referred to as 110). With this solution, each (1) longwall has only one (1) roadway without (0) a protected coal pillar. The essence of technological solution is that the preparation roadway of longwall is maintained without the support of coal pillars or artificial pillars. Roadways maintained by the overall solution are actively implemented to reduce the pressure while enhancing its load capacity. Firstly, directional pre-splitting roof cutting is used to cut down the transmission passage of ground pressure in part of the overlying rock strata. The gob-side roadway should be maintained by cable bolt or anchor with Constant Resistance and Large Deformation (CRLD) to keep the gateway roof stable during the advance roof caving. Finally, the gangue of the gateway roof will be blocked by using hydraulic props and barbed wise, which are closed to the gob-side (Figure 4).

However, solution 110 also has some disadvantages:

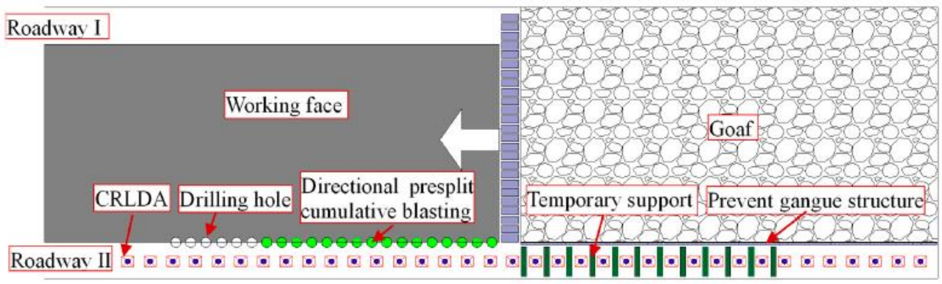
- The protected side of the roadway contacts directly to the mining area with poor isolation. If the site is highly affected by water and coal is self-igniting, safety becomes critical.

- The technological method is only effective for mining coal seams with thickness from thin to medium (≤ 3.5 m) and dip up to 15°.

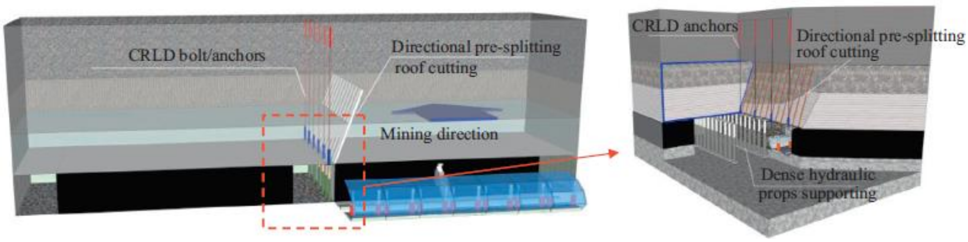


a. Preparation diagram of type 121 *b. Preparation diagram of type 111*

Fig. 3. Illustration of the preparation for longwall mining type 121 and 111.



a. Coal mining diagram in preparation roadway - longwall type 110



b. Diagram of layout principles because cable belt increase the ability to carry the load of the roadway along the seam and arrange the hole to cut the main roof

Fig. 4. Illustration of the preparation roadway for longwall mining type 110.

Preliminary assessment, both mining solutions 111 and 110 can be applied in underground coal mines in Quang Ninh province to reduce coal loss and the costs associated with the preparation roadways, discounting the mine depreciation, thereby contributing to lower production costs. In Quang Ninh, most coal seams have thicknesses over 3.5 m and dip angles over 15°. Furthermore, due to a specific tropical climate, long annual rainy season, and a large amount of rainfall, many mines scope risks when exploiting the upper floors, such as collapse rock walls or displacing cracks to connect the surface to the terrain. Hence, there is a problem of surface water infiltrating/flowing into the mining area, then exporting to the lower mining floor is inevitable. Besides, some mines face fire problems in the excavation due to arising spontaneous combustion of coal (such as Ha Lam and Uong Bi mines). Thus, solution type 111 is widely used owing to the good isolation of the roadway, which is protected with the previous mining area.

Figure 5 illustrated the results of the application of solution type 111 in Changcun mine (China) [4]. The strip pillar is applied to protect the transport roadway of the longwall S511 as a ventilation roadway of the lower longwall (S510). The transport roadway has a rectangular section, 4.5 m wide, 3.5 m high, resisting by reinforced plastic anchors combining cable anchors on the roof of the roadway. The coal seam has a thickness of 6.1 m, dip angle of 4°. The roadway was driven along the seam floor. On the roof of the roadway is a layer of coal with a thickness of 2.6 m.

Artificial pillars protecting roadways are formed from a mixture of mineralized materials labeled C30 (30 MPa - compressive strength, 30 GPa - elastic modulus, Poisson coefficient 0.2, see Table 2). The artificial pillars strip is 1.6 m wide, 3.5 m high, located in the mining area, and is contacting the transport roadway. The artificial pillars consist of blocks (3.0 m × 1.6 m × 3.0 m), constructed adjacent to each other using a specialized mold bag of the same size. The mixture of materials is pumped into the bag. To increase the load capacity is steel bolt is added to the artificial pillars strip through its body. With the length of the experimental roadway of 300 m in the Changcun coal mine, 100 bags were used, corresponding to 100 artificial pillars forming artificial pillars strip.

Tab. 2. Specifications of some types of construction materials for pillars.

Type	Young's Modulus	Poisson's Ratio	Compressive strength	Tensile strength
C10	20 GPa	0.2	10 MPa	0.75 MPa
C20	25.5 GPa	0.2	20 MPa	1.1 MPa
C30	30 GPa	0.2	30 MPa	1.45 MPa

Fig. 5. Artificial pillar protecting transportation roadway of longwall S511 in underground coal mine Changcun, China.

The monitoring results show that the most considerable mine pressure impacts the pillar at the range of 5.0 m from the longwall face, reaching 37–37.9 MPa, gradually decreasing to about 30 MPa at the position of 60 m away from the face (Figure 6). In general, the solution has been successfully applied with the following consequences: the mine pressure on the pillar range is at the allowed level, and the pillar strip meets the protection and maintenance requirements of the transport roadway of longwall S511. Along with the technical efficiency, the solution also brings economic benefits to Changcun mine through saving coal

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resources and reducing preparation roadway costs. More importantly, with only 300 m of roadway kept as a ventilation roadway for the next longwall, this mine saved about 638 thousand USD.

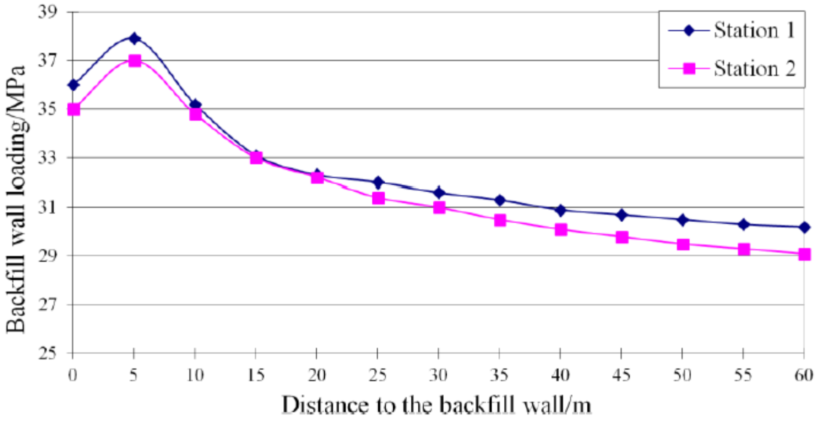

Fig. 6. Mine pressure changes acting on artificial mine pillars in Changcun.

3.2 Potential of applying the technological solution in underground mines in Quang Ninh province

According to [9], coal reserves of seams, with medium thickness (from 1.2–3.5 m with about 184,327 thousand tons), thickness over 3.5 m (about 280,080 thousand tons), and dip up to 35° are mobilized and operated in 12 large underground mine projects in Quang Ninh province (Mao Khe, Uong Bi, Vang Danh, Nam Mau, Ha Lam, Nui Beo, Ha Long, Quang Hanh, Duong Huy, Thong Nhat, Khe Cham and Mong Duong). The total reserves account for 464,407 thousand tons, nearly 74% of total coal reserves (630,645 thousand tons - only in the longwall area, details shown in Figure 7). This is the range of reserves expected to apply the longwall mining technology, protecting the roadway along the seam strike by coal pillar. If only temporarily calculated by 12% of the coal reserves in the longwall mining area, the coal reserves left in the protection pillars were 55,729 thousand tons (22,119 thousand tons of average thick seams, 33,610 thousand tons of thick seams). This reserve equivalent equals to total reserves of a large underground mine. Thereby, there is a potential of applying new technology solutions (111 and 110) for mining coal in protected pillars of underground coal mines in Quang Ninh province, and suitable to the strategy of Vietnam coal sector.

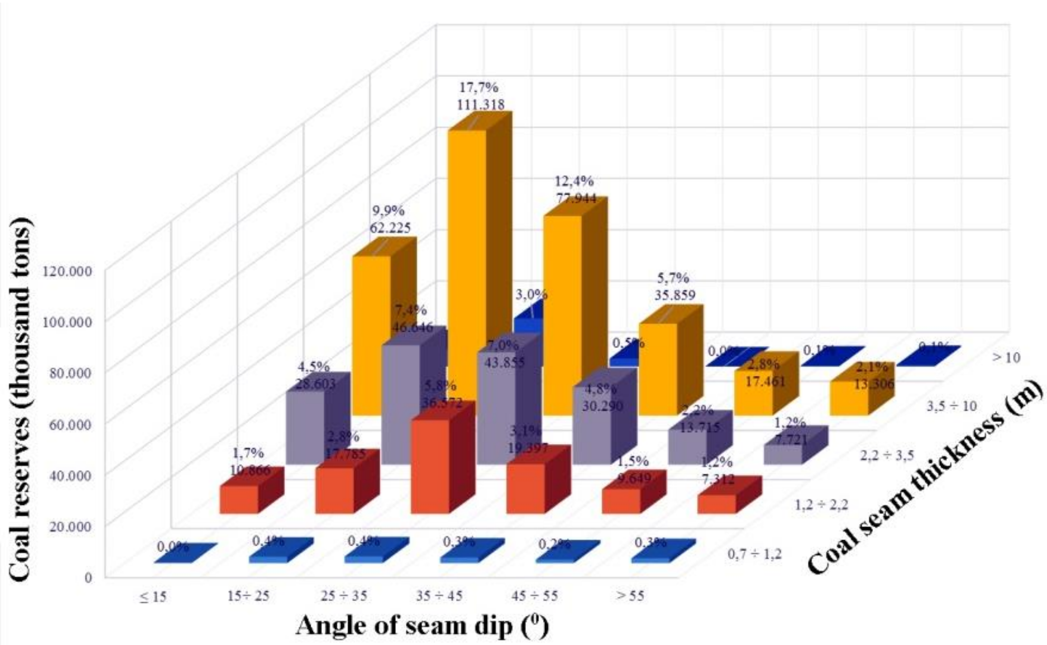

Fig. 7. Coal reserves of 12 underground mine projects in Quang Ninh province [9].

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4. Implementing and evaluating the effectiveness of artificial pillars to replace coal pillars protecting prepared roadways in underground coal mines

4.1 Choose the location and design to apply artificial pillar

To accurately assess the efficiency of using artificial pillars to protect the preparation roadways, the authors calculated and designed a specific underground mine of VINACOMIN. The selected design site is a longwall 14.5-19 level -190/-150 of seam No 14.5, Khe Cham III coal mine of Khe Cham Coal Company - VINACOMIN. The thickness of the coal seam design is 5.6 m. The dip angle is 12°. The floor and roof of the longwall are stable aggregates of rock. The longwall ranks type I of methane gas, and the coal of seam is not spontaneous combustion. According to the plan of Khe Cham Coal Company, the longwall is prepared with a face length of 65 m and the strike length of 171 m. A coal pillar of 18 m width remains to protect and maintain the transport roadway as a ventilation roadway for the next longwall (14.5-20) (Figure 8). Then, the actual length of the longwall is only 45 m.

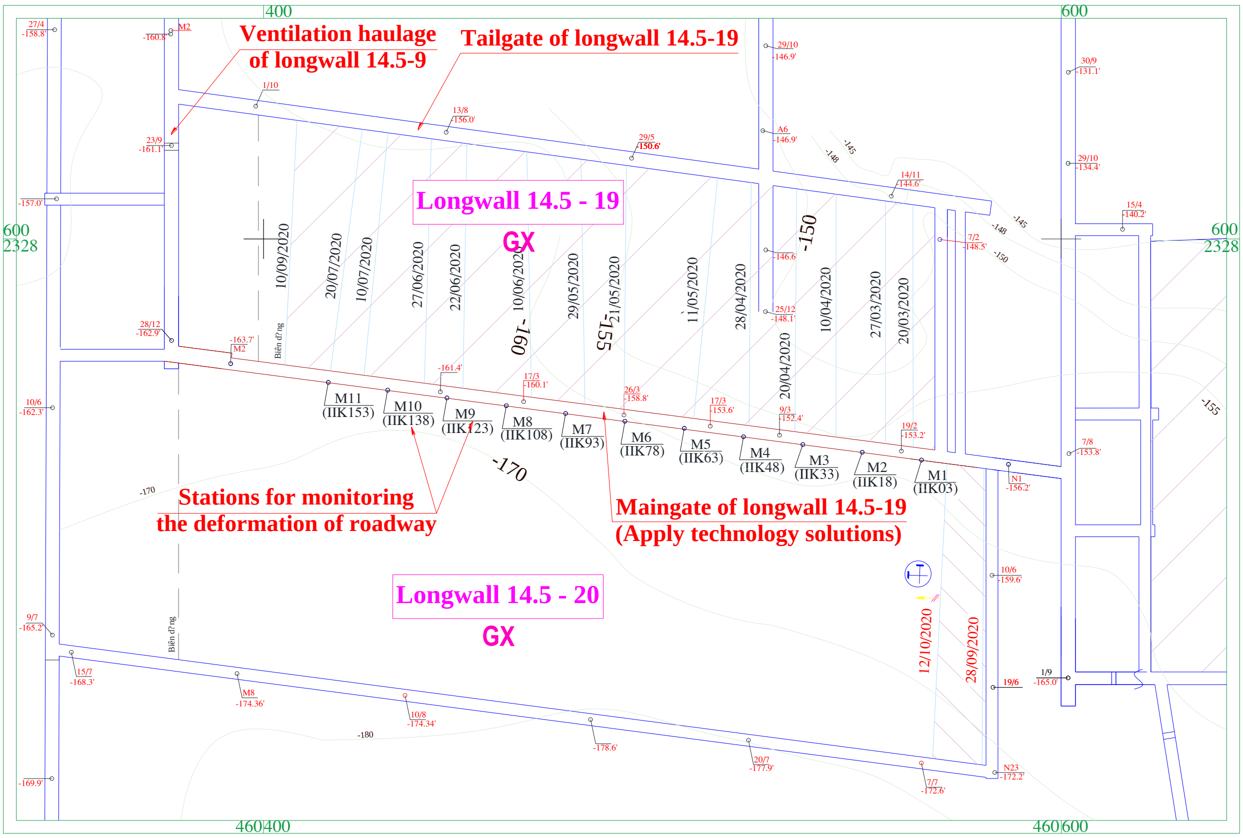

Fig. 8. Location map of the designed longwall 14.5-19 in Khe Cham coal mine III.

The transport roadway of longwall 14.5-19 was driven along the seam floor and lies entirely in the seam 14.5 with arch cross-section (3.24 m high, 4.03 m wide, excavated area 11.2 m^2, and usable area 8.5 m^2). This roadway is supported by flexible anti-steel. The structure consists of 5 SVP-27 steel sections with a wave of 0.5 m. Because the transport roadway within the coal seam is large, it is not suitable to apply artificial pillars made from stone strips, supporting pillars, or mining without protective pillars. Accordingly, in this case, artificial pillars with continuous strip and crib construction are applicable.

The longwall 14.5-19 had been completed and must be put into operation soon at the time of evaluation. The authors assessed the current technical conditions, the ability to supply materials for reinforcement, and the production progress in the longwall 14.5-19 of coal seam 14.5. At the results, the authors chose artificial pillars with wooden crib structure combined with steel columns (pillar structure made of more modern and superior materials will be deployed later). Accordingly, the intersection of the longwall will be supported and kept by the cribs with suitable compression capacity. At the same time, the inside area of the transport roadway of longwall 14-5-19 also needs additional reinforcement. The application will allow the company to mine more coal in pillars protecting the prepared roadways (about 19,951 tons). The coal output of the design longwall increased to 67,451 tons. The rate of coal loss from 39% decreased to 14%. The roadway

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per 1000 tons decreased by nearly 23%, from 8.19 m per 1000 tons to 6.3 m per 1000 tons. Figure 9 illustrates the schematic constructed support the transport roadway of longwall 14.5-19 and artificial pillars. Table 3 shows some technical and economic indicators of the technology.

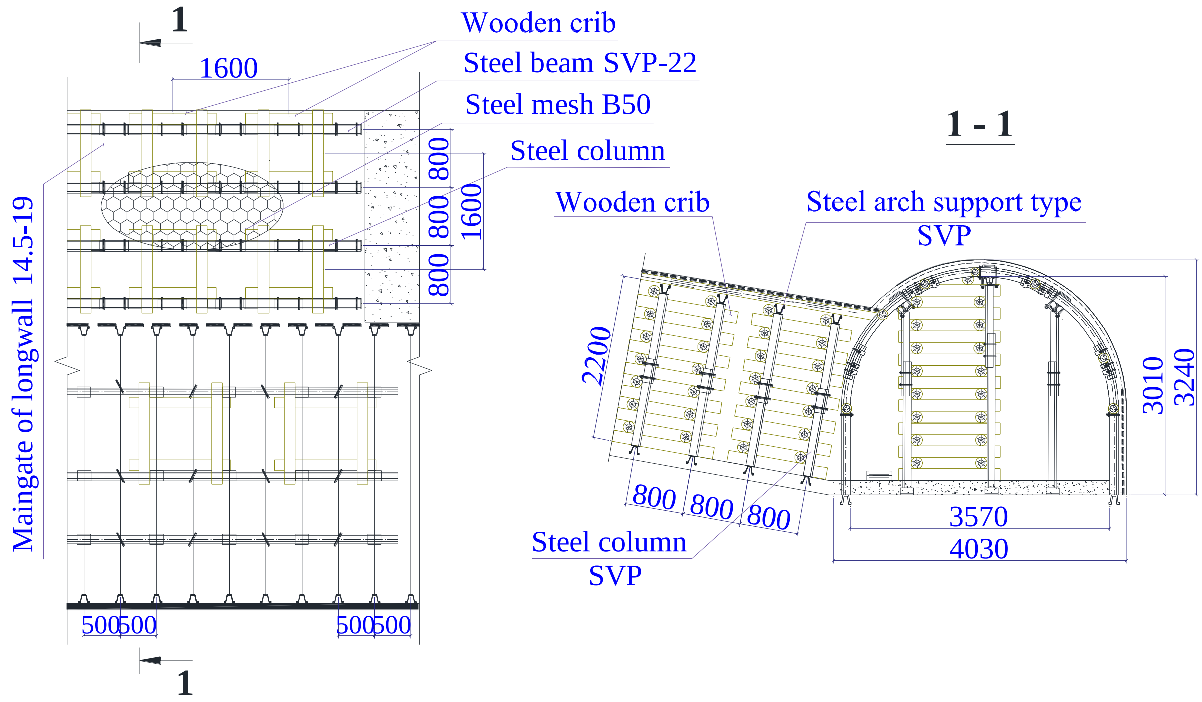

Fig. 9. Illustration of artificial pillars constructed in underground.

Tab. 3. Summary of main economic and technical indicators for longwall according to the options of protecting the transport roadway 14.5-19.

No	Name of indicator	Unit	Amount		Difference (increase '+'; reduction '-')
			Leaving protection coal pillar	*Using artificial pillar*	
1	*2*	*3*	*4*	*5*	*6 = 5-4*
1	Coal seam thickness	m	5.60	5.60	
2	The dip angle of the coal seam	degree	12	12	
3	Face length	m	45	65	+20
4	Length of coal pillars protecting the transportion roadway	m	18	0	-18
5	Length in retreat longwall	m	171	171	0
6	Coal reserves				
a	of the design area	thousand tons	81,255	81,255	0
b	of coal pillar protecting transportation roadway	thousand tons	25,807	-	-25,807
c	of the design longwall	thousand tons	61,442	87,249	+25,807
7	Volume meter of preparation roadway from designed area	m	432	472	40
8	Mining capacity	ton/year	150,000	150,000	0
9	Equipment depreciation time	year	5	5	0
10	Output of coal extracted from designed longwall (technology coal loss 5%)	ton	52,777	74,945	+22,168
11	Cost for a meter of preparation roadway	m/1000 ton	8.19	6.30	-1.89
12	Coal loss rate	%	39%	14%	-25%
13	Coal commercial product	ton	47,500	67,451	+19,951

In the economic aspect, the price of one ton of consumption coal in traditional pillars to protect the transport roadway is 1,617,844 VND. Using artificial pillars to replace coal pillars makes it possible to reduce the costs of driving roadways, infrastructure depreciation, and mining rights fees by mining more coal reserves from the pillars. Therefore, the price can be reduced to 1,583,929 VND per ton. Thus, for each ton of mined coal from the longwall 14.5-19 using artificial pillars, Khe Cham Coal Company can benefit 33,915 VND. The total benefit value for Khe Cham Coal Company in just one area of the longwall 14.5-19 is calculated by 67.45 thousand tons × 33,915 VND per ton = 2,287,610 thousand VND (about 83,185 Euros). Table 4 and Figure 10 show details of economic indicators's comparison.

Tab. 4. Comparison of economic indicators between two options.

No	**Name of indicator**	**Unit**	**Amount**		**Difference (increase '+'; reduction '-')**
			Leaving protection coal pillar	***Using artificial pillar***	
1	*2*	*3*	*4*	*5*	*6=5-4*
1	Coal commercial product	Ton	47,500	67,451	+19,951
2	Total cost of coal production	million VND	76,847	106,837	-29,990
3	Coal price	VND/ton	1,617,844	1,583,929	-33,915
-	Cost for driving roadways	VND/ton	165,777	126,440	-39,337
-	Cost of coal mining in longwall	VND/ton	421,436	511,660	+ 90,224
-	Cost of depreciation of mine opening and infrastructure	VND/ton	152,451	107,358	-45,093
-	Cost for mining rights	VND/ton	37,259	26,238	-11,021
-	Others	VND/ton	840,922	812,233	-28,688
4	Total benefit value of the artificial pillar option (V.1 x VI.3)	thousand VND	**2,287,610**		

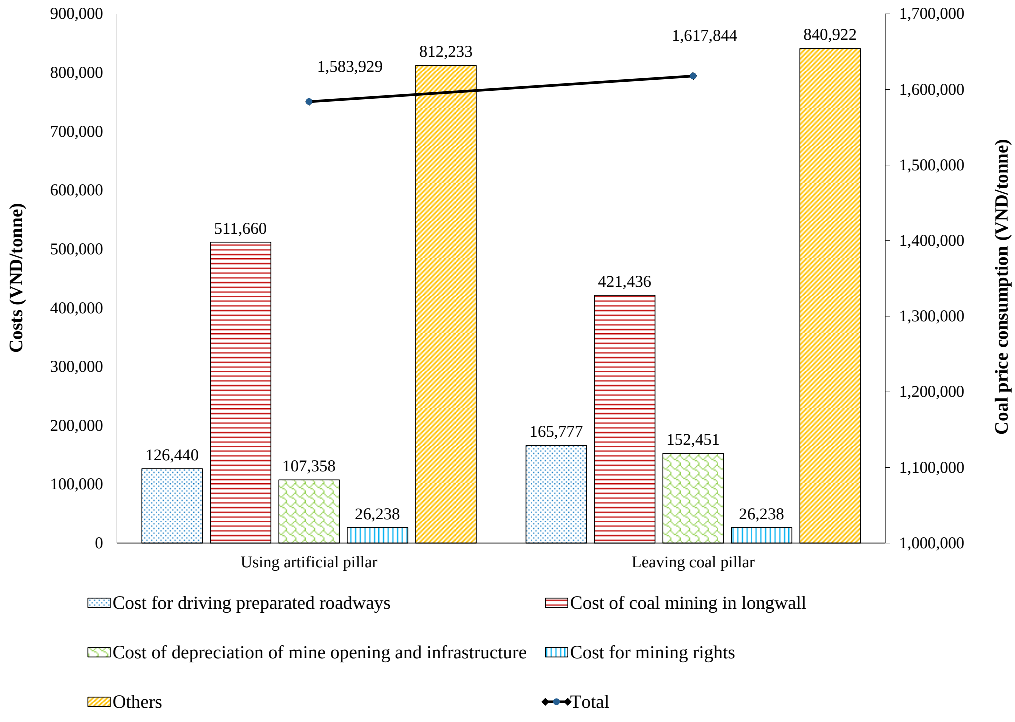

Fig. 10. Comparison of consumption price between two technological solutions.

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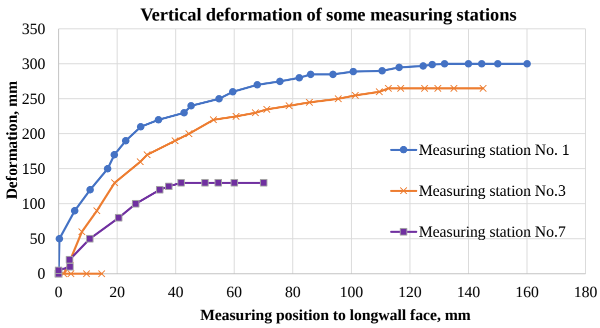
4.2 Evaluating the stability of the roadway protected by artificial pillars

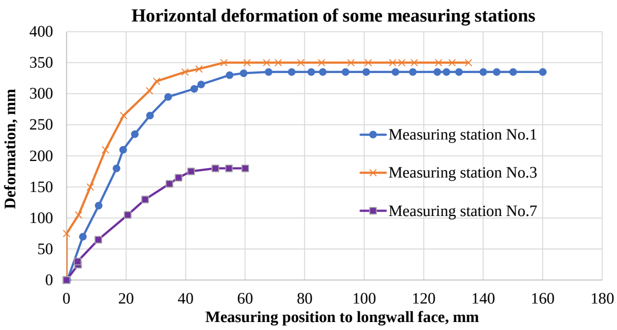
To evaluate the stability of the transport roadway protected by artificial pillars, during the exploitation of longwall 14.5-19, the authors collaborated with Khe Cham Coal Company to set up stations monitoring deformation on the transport roadway of longwall 14.5-19. There are 11 measuring stations located at a distance of 3, 18, 33, 48, 63, 78, 93, 109, 123, 138, and 153 meters from the first position of longwall face 14.5-19 along the strike to the last mining position.

The monitoring results show that the roadway's deformation rate was the strongest and fastest within about 40 m in front of and behind the longwall face (vertical deformation rate was from 7 to 10 mm/day-night; horizontal deformation from 8 to 20 mm/day-night). In the advanced direction of the longwall face, in the gob area from the 40th meter in the opposite direction of the face forward, this rate gradually decreased (the vertical deformation rate was only from 0 to 4 mm/day-night, vertical deformation from 0 to 6 mm/day-night). From the 100th meter behind the longwall face towards the gob, the roadway was no longer deformed and became stable.

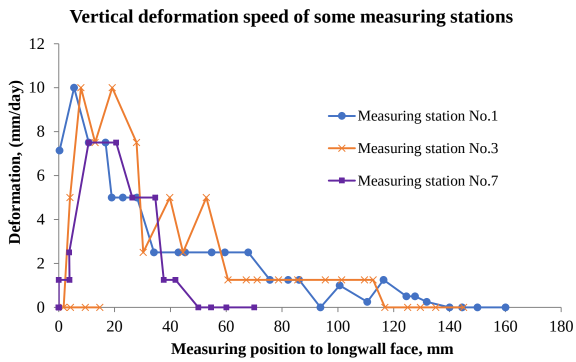
The total deformation value of the roadway during the monitoring period reached a maximum of 300 mm vertically (measurement station No.1) and 350 mm horizontally (measurement station No. 3). It corresponds to a reduction of its cross-section of about 9.8–9.97%, ensuring the parameter according to safety regulations to serve ventilation and production of the longwall 14.5-20 (see Figure 11).



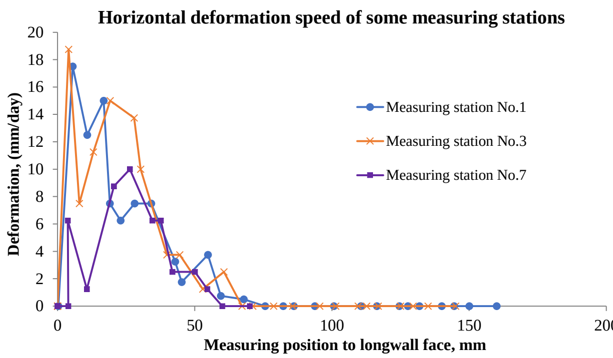
a. Degree of vertical deformation



b. Degree of horizontal deformation



c. Vertical strain rate



c. Horizontal strain rate

Fig. 11. The result of deformation monitoring of roadway, longwall 14.5-19.

5. Conclusions

Applying artificial pillars to replace coal pillars protecting prepared roadways during the mining process will reduce the loss of coal resources, the cost of driving roadways, and direct labor. Therefore, the company can gain better economic efficiency. New underground coal mines' investment requires many procedures and cannot be deployed soon. Thus, it is an excellent way to apply different mining technology with a high level of mechanization and significant capacity to meet the increasing coal demand of the country. The technological solution using artificial pillars to replace coal pillars protecting the prepared roadway can potentially ensure the sustainable development goal of VINACOMIN and Vietnam's coal industry regarding economic benefits, the utilization of coal resources, and the safety of the labor.

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