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CONSTRUCTION OF NEW MULTI-FUNCTION TYPE ARTIFICIAL BOUNDARY PILLAR FOR TRANSITION FROM OPEN PIT TO UNDERGROUND MINING

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ABSTRACT

In allusion to the defects of large material consumption and high construction cost of conventional artificial boundary pillar for the transition from open pit to underground mining, a new multi-function type of artificial boundary pillar scheme of reinforced concrete is proposed, which creates favourable conditions for underground mining below the pillar and stacking tailings over the pillar. We established the mechanical model of the artificial pillar, and use MIDAS-FLAC3D software to analyse the stability of the artificial pillar. The result shows that the multifunctional artificial pillar has good impervious control and flood control characteristics and bearing capacity, and can effectively separate the influence between the open pit and the underground, which realizes the effective utilization of resources and greatly improve the economic efficiency of mines. At the same time, the tailings in the open pit will support the open slope and enhance the stability of the slope. Moreover, this method effectively reduces the area of tailings reservoir and has good ecological and environmental protection value, which can provide useful reference for related mines.

KEYWORDS

Multi-function; Artificial boundary pillars; Open pit; Underground mining; Tailings

INTRODUCTION

When open pit mining is transited to underground, boundary pillar is the critical safety insurance [1-3]. Boundary pillar could not only avoid mutual impact of the open pit production and underground production, such as blasting vibration, pit water flooding underground, etc., but also benefit the enclosed air ventilation system of underground mining. On the other hand, the boundary pillar could also give supports to side slopes of the open pit. Moreover, in a transition period, if the boundary pillars are too thin, there will be a risk of sudden fall of slope, which might lead to a waste of mineral resources and great economic loss.

Along with the sinking of the exploration, stripping ratio will increase accordingly. When stripping ratio exceeds optimal economic stripping ratio, most of the mines will convert open pit mining to underground, with an intention to cut exploration cost [4-6]. During the transition period, to minimize or isolate the impact of open pit production towards underground mining, 2 alternatives will be taken conventionally: one is that the boundary pillars with a certain thickness are left at the bottom of the pit, which is isolated from underground production; the other is to cave side slope or backfilling waste to form a waste layer to isolate open pit production with underground mining. However, due to the loose structure and uneven particle size of the deposit, the isolation performance is poor, and it usually causes a burden for underground water drainage, flood prevention and ventilation system as well.

Compared with the natural artificial boundary pillar, the artificial boundary pillar structure not only has its function, but also can recover the security pillar resources in advance, and can resolve resources supply during the transition period, and greatly improve backstopping efficiency and reduce grade deterioration of resources. Artificial pillars are reinforced concrete structures with strong integrity and high bearing capacity, and their strength and stability are 2-3 times higher than those of natural boundary columns. It supports side slope better, and anti-seepage and anti-leakage performance enjoy advantages as well. In addition, heap leaching slag and tailings can be installed at the top of the artificial boundary column to save the area occupied by the dump and tailings dam, which has good ecological and economic benefits.

MECHANICAL MODEL

One of the keys to analyse the stability of boundary pillar in the process of transforming the open pit into underground mining is to establish an appropriate mechanical model for mechanical analysis of the structure [7]. According to the stress characteristics of the roof in underground mining, it can be regarded as an elastic foundation beam. As shown in Figure 1, we define as follows: the width of the beam model on the elastic foundation of the local boundary pillar is L, which is a rectangular beam with an equal section length. Under the action of loading $q(x)$, the counterforce between the foundation and the beam is $\sigma(x)$, and the subsidence of the foundation and the beam is $y(x)$. When calculating the internal force of the local boundary pillar model, the subsidence function $y(x)$ is the basic unknown quantity. The calculation model selects the coordinate system XOY, the positive and negative sign of deformation, load and internal force as shown below.

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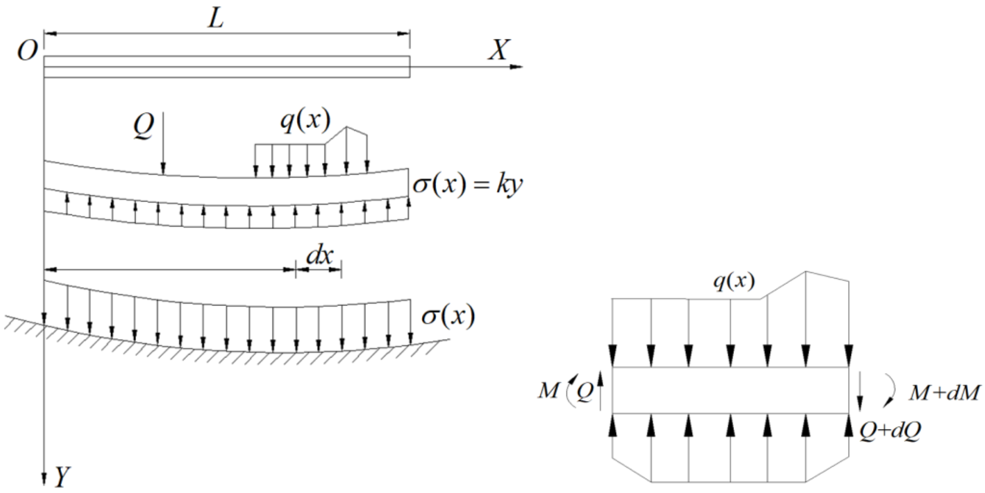

Fig.1- Microelement analysis of the boundary pillar model

It is assumed that a microelement segment dx is intercepted in the beam, the following formula is obtained according to the vertical equilibrium condition:

$$\sum Y = Q-(Q+dQ)+kydx-q(x)dx=0 \tag{1}$$

After simplifying the calculation, the following formula can be obtained:

$$\frac{dQ}{dx}=ky-q(x) \tag{2}$$

According to the moment equilibrium condition, the following result is obtained:

$$\sum M = M-(M+dM)+(Q+dQ)dx+q(x)\frac{(dx)^2}{2}=0 \tag{3}$$

After omitting the second order derivative, the following formula is obtained as:

$$Q=\frac{dM}{dx} \tag{4}$$

After solving the derivative of the above equation, and substitute the result into the Equation (2), the result is obtained as below:

$$\frac{dQ}{dx}=\frac{d^2M}{dx^2}=ky-q(x) \tag{5}$$

If the deflection y of the beam and the angle θ of any section of the beam are known, then the bending moment and shear force can be calculated according to the formula in mechanics of materials, that is:

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$$\begin{cases} \theta = \dfrac{dy}{dx} \\ M = -EI\dfrac{d\theta}{dx} = EI\dfrac{d^2y}{dx^2} \\ Q = \dfrac{dM}{dx} = -EI\dfrac{d^3y}{dx^3} \end{cases} \tag{6}$$

When the artificial boundary pillar is regarded as a beam on the elastic foundation, the internal force of the beam is calculated by the theory of elastic foundation beam, and the equation of internal stress is:

$$\begin{cases} \sigma_x = \dfrac{6(q+\rho gh)}{h^3}(l^2-x^2)y + \dfrac{(q+\rho gh)y}{h}(\dfrac{4y^2}{h^2}-\dfrac{3}{5}) \\ \sigma_y = \dfrac{\rho gh}{2}(1-\dfrac{4y^2}{h^2}) - \dfrac{q}{2}(1+\dfrac{y}{h})(1-\dfrac{2y}{h})^2 \\ \tau_{xy} = -\dfrac{6(q+\rho gh)}{h^3}(\dfrac{h^2}{4}-y^2)x \end{cases} \tag{7}$$

According to the beam theory of elastic foundation, the shear and bending moment of the beam section can be calculated, then the stress distribution on any cross section of the beam can be obtained from the above formula, and the stability of the beam can be evaluated and analysed according to the strength criterion.

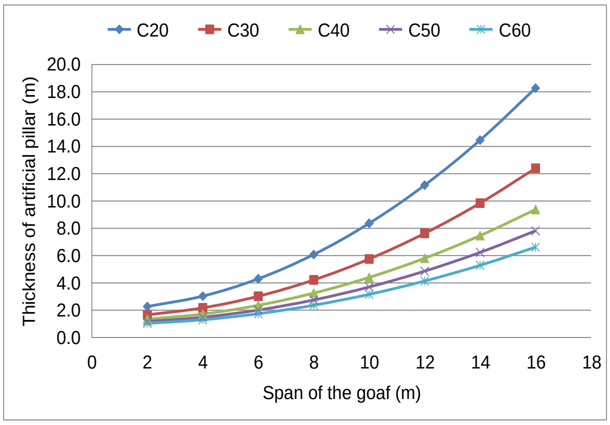
THEORETICAL CALCULATION OF THE THICKNESS OF THE ARTIFICIAL PILLAR

There are many theoretical calculation methods for calculating the safe thickness of boundary pillar, several of the commonly used methods are as follows [8]-[9]: (1) K.B.'s formula. (2) B.И.'s formula. (3) Plate beam theory. (4) Protodyakonov ground pressure theory. (5) Engineering calculation method. (6) Material mechanics method. This paper summarizes the principles and applicable conditions of various theoretical methods for calculating artificial pillars, and its engineering analytical method is shown in Table 1.

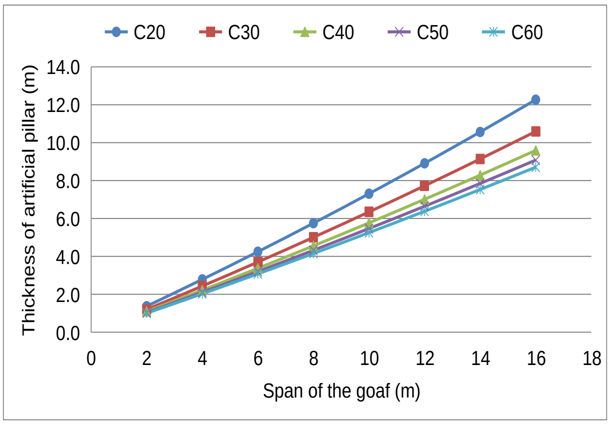
Tab.1 - Summary of engineering method for calculating safety thickness of artificial pillars

Method type	Calculation principle and consideration factor
K.B.'s formula	The effects of goaf span and rock properties (strength and structural failure characteristics) on boundary pillar is considered, and the influence of working equipment on the bench is also considered.
B.И.'s formula	The effects of goaf span, boundary rock mass characteristics (tensile characteristics) and dynamic load of bench blasting are considered.
Plate beam theory	Assuming that the boundary pillar is a slab beam fixed at both ends, according to the theory of material mechanics, the formula for calculating the thickness of the safety boundary pillar is derived.
Engineering calculation method	The basic principle is to simplify the calculation of complex three-dimensional thick plates as the plane problem of idealized elasticity theory.
Material mechanics method	The boundary pillar is regarded as a simply supported beam, and the thickness of the beam under ultimate load is calculated.

The above methods are used to calculate the thickness of artificial boundary pillar according to different strength concrete (C20, C30, C40, C50, C60, they mean that the compressive strength of concrete is 20MPa, 30MPa, 40MPa, 50MPa, 60MPa, respectively.), and the calculated results are shown in the following figures.



(a) K.B.'s formula



(b) Plate beam theory

Fig.2 - Artificial pillar thickness calculated by different theories and methods

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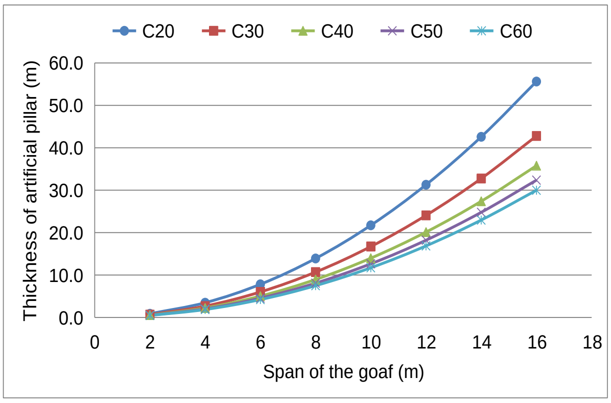
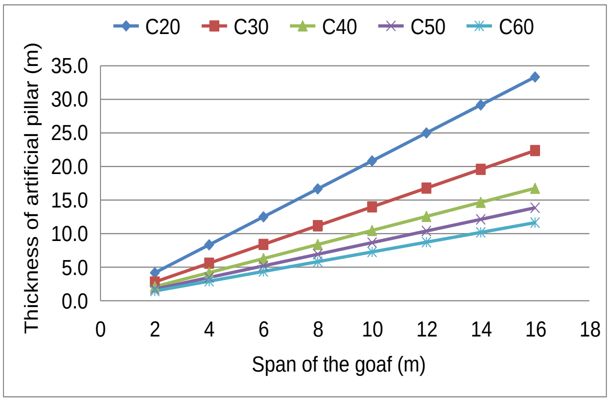
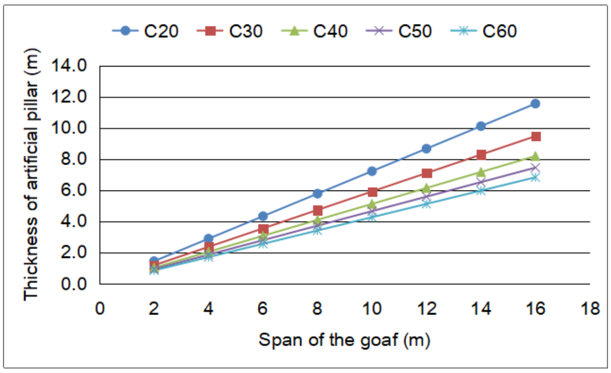


(c) Engineering calculation method



(d) Protodyakonov ground pressure theory



(e) Material mechanics method

Fig.2 - Artificial pillar thickness calculated by different theories and methods

It can be seen from Figure 2 that the thickness of the artificial pillar decreases with the increase of the concrete strength, and increases with the increase of the goaf span. Through the technical and economic analysis, it is considered that C40 strength concrete is better. For the C40 strength concrete artificial pillar, we calculated the required thicknesses under different spans by different theories and methods. See Table 2 and Figure 3.

Tab.2 - Artificial pillar thickness calculated by different methods under different span of goaf

Calculation method and theory	Span of the goaf /m							
	2	4	6	8	10	12	14	16
K.B. formula	1.3	1.7	2.4	3.3	4.4	5.8	7.5	9.4
Plate beam theory	1.1	2.2	3.4	4.6	5.8	7.0	8.3	9.6
Engineering method	0.6	2.2	5.0	8.9	14.0	20.1	27.4	35.8
Protodyakonov ground pressure theory	2.1	4.2	6.3	8.4	10.5	12.6	14.7	16.8
Material mechanics method	1.0	2.0	3.1	4.1	5.1	6.1	7.2	8.2

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As can be seen from Figure 3, the calculation of the numerical values by K.B., Plate beam theory and Material mechanics method are very close, and the theoretical analysis accords with the engineering practice. However, because the Loose coefficient theory and the Protodyakonov ground pressure theory do not take into account the stress conditions of artificial pillars, the accuracy of the calculation is not high. Also, the engineering calculation method is a simplified calculation method, which ignores the external influence factors, and calculates accurately and is not worth trusting. In this paper, the calculation results of K.B. formula., Plate beam theory and Material mechanics method are used as reference and comparison. In order to ensure the reliability and accuracy of the calculation, numerical simulation and elastic foundation beam theory are used for further calculation and verification.

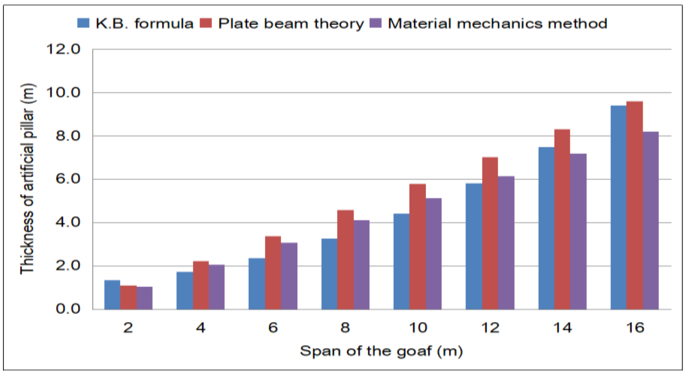

Fig.3 - Similar calculation results of artificial pillar thickness

DESIGN OF ARTIFICIAL PILLAR

Engineering background

The upper ore body of a gold mine is taken by open-pit mining. The maximum size of open stope is 881m×168m, and the maximum vertical depth of open stope is 57 m. Underground mining and main ramp exploitation system are adopted in the underground mine, and the mining method is sublevel open stopping and subsequent filling with the mining in order from the bottom to the top, see Figure 4. In order to ensure the independence of underground mining and tailings stacking in open pit and ensure the safety of underground mining and tailings rejection, it is necessary to set up artificial boundary pillar.

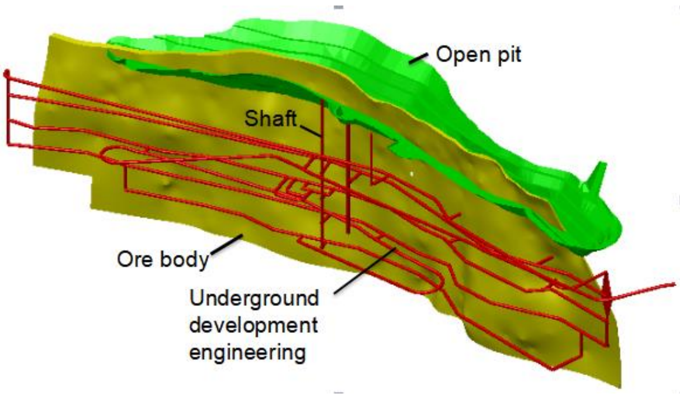

Fig.4 - 3D design model of transition from open pit to underground mining

Design range of artificial pillar

According to the mining technical conditions, artificial bottom width, stability state of the open pit slope, mine hydrogeology and other factors, the design of the artificial pillar is divided into five areas: *A, B, C, D* and *E*. The distribution characteristics of artificial pillars in various regions are shown in Table 3 and Figure 5.

Tab.3 - Subarea characteristics of the artificial pillar in a gold mine

Subarea name	Location	Width (m)	Length (m)
A	9S~19	6	213
B	0~9S,32~42,18~20	10	300
C	0~10S	8	163
D	12~18	22	80
E	28~32	12	61

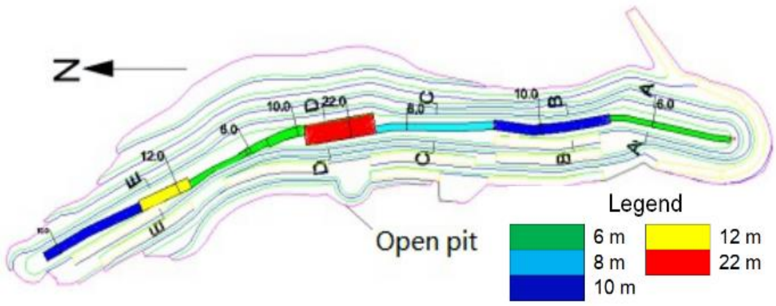

Fig.5 - Layout plan of artificial pillar

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Structure of an artificial pillar

After completion of open pit mining, short hole and minor delay blasting will be adopted at bottom of the open pit to provide an even slope for artificial pillar construction. The artificial pillar uses reinforced concrete structure, to connect with reinforced concrete artificial pillar with anchor bolt and integrate with wall rock. Due to long distance of the open pit bottom, the artificial pillar will be constructed in steps and layers to form an integrated structure at the end. It cannot only improve stability of the boundary pillar, but also get portion of the ores to ensure stable transition from open pit production to underground mining. The schematic diagrams of artificial pillar structure are shown in Figure 6. and Figure 7.

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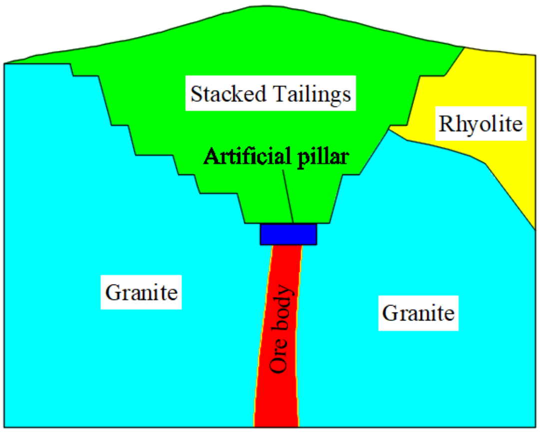

Fig.6 - Structure arrangement of artificial pillar

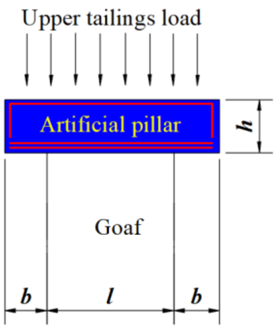

Fig.7 - Magnifying structure of artificial pillar

Isolation and cushion layer of artificial pillar

In order to avoid possible cracks in the pillars of artificial boundary and prevent surface water from penetrating into the underground, the upper layer is provided with an isolation layer. The structure of the isolation layer is 100 mm thick powdery rock and 0.5mm thick geomembrane above it. It can also lay 0.5mm thick geotextiles, plus a layer of agricultural film. In order to prevent the blasting damage to the artificial pillar structure when the underground ore body is being mined, the blasting cushion is left at its bottom. The cushion is made up of gravel, which is placed above the ore body before the construction of artificial pillars. See Figure 8.

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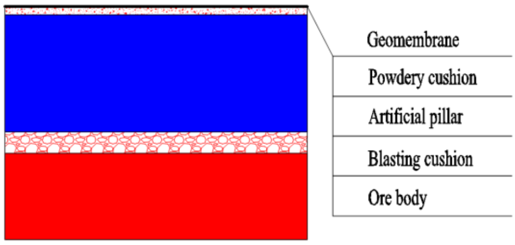

Fig.8 - The upper isolation layer and the lower cushion structure of artificial pillars

STABILITY ANALYSIS OF ARTIFICIAL PILLAR

In practical application, the factors affecting the thickness of the artificial boundary pillar mainly include the span of the goaf, the physical and mechanical parameters of the ore and rock, the mining order, the engineering geology and hydrogeology of the rock mass, and the condition of the original rock stress and so on. However, some factors can only be considered in theoretical calculation, which often leads to a certain gap between the calculation results and the actual situation [10]-[11]. In order to make the calculation result closer to reality, comprehensively considering the factors affecting the stability of artificial pillars, the FLAC3D software is used to simulate the artificial pillar under different spans to ensure that the parameters of the boundary structure are more reasonable.

Mechanical parameters of rock mass

Physical and mechanical parameters of the ore rock are the basic parameters of numerical simulation. The accuracy of numerical simulation results depends on whether the parameters values are correct or not. Generally, the mechanical parameters of rock are obtained by the rock mechanics test under ideal conditions, and then it can be used for numerical simulation after the test data are reduced by the Hoek-Brown criterion, The rock mass parameters after deducted in this paper are shown in Table 4.

Tab.4 - Rock mass parameters after being deducted

Lithology	Bulk modulus(GPa)	Poisson ratio	Tensile strength (MPa)	Cohesion (MPa)	Friction Angle (°)
Granite	4.16	0.19	3.71	4.93	32.40
Ore body	4.16	0.19	3.71	4.93	32.40
Rhyolite	1.28	0.30	0.96	3.70	39.93
Tailings	0.05	0.10	0.10	0.07	18.50

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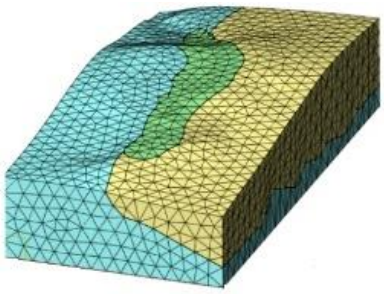
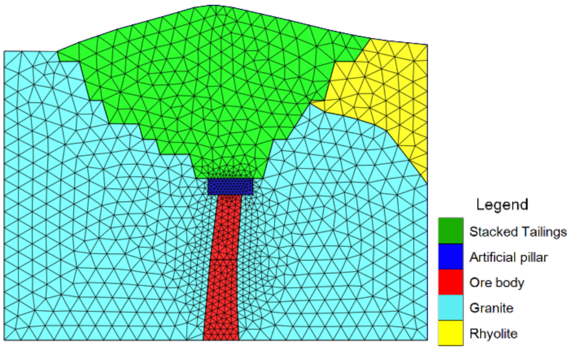
Numerical simulation calculation

The 3D numerical calculation model and typical section model of the mining area are established by using MIDAS software. See Figure 9.



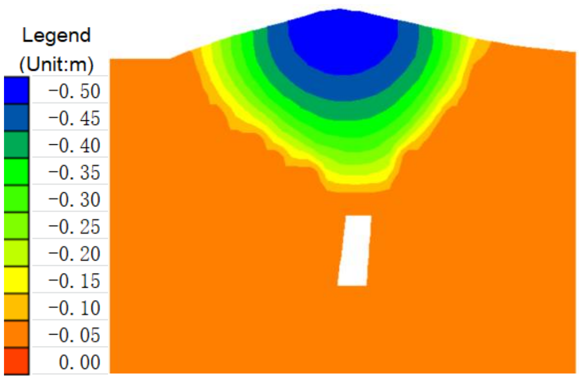
(1) 3D model of mine



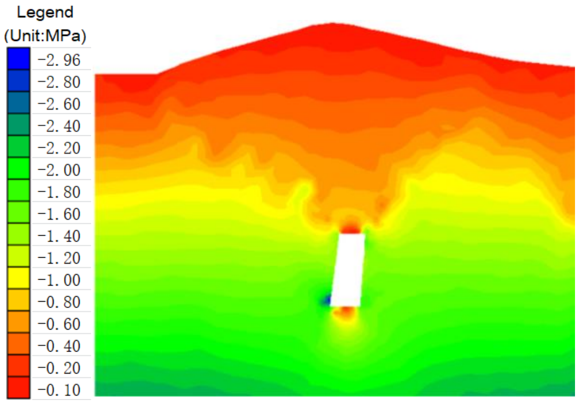
(2) Section model of mine

Fig.9 - The numerical simulation model based on MIDAS software

In order to comprehensively study the safety thickness of artificial pillars under different spans, the numerical simulation of the artificial pillars stability under different spans (6~22 m) was carried out by FLAC3D. Taking the goaf with a span of 7 m and a height of 20 m as an example, the models of artificial pillar thickness of 3m, 4m, 5m, 6m and 7 m are constructed respectively. Moreover, the stress state and artificial pillar safety state of 5 goaf models are studied and analysed. Figure 10 shows the displacement and stress cloud map of the mine section.



(a) Distribution diagram of vertical displacement



(b) Distribution diagram of vertical stress

Fig.10 - The results of calculation by using FLAC3D software

When the span of the goaf is 7 m, the maximum displacement of artificial pillars at different thicknesses is shown in the Figure 3. It is shown that the displacement of the artificial pillar is inversely proportional to its thickness.

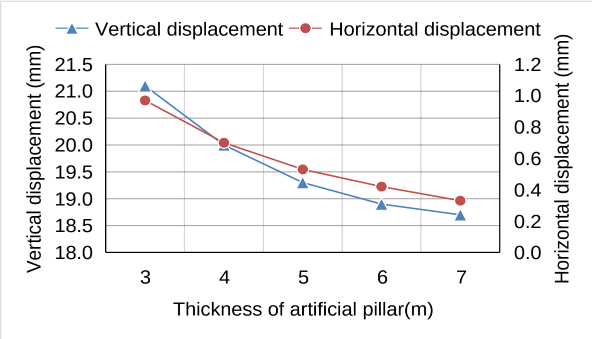


Fig.11 - The maximum displacement of artificial pillars at different thicknesses

The principle of Griffith criterion is that the failure of rock is caused by tensile stress [12]-[15]. Since the tensile stress is the most important factor determining the stability of the mined out area, this paper mainly analyses the influence of tensile stress on artificial pillars. It can be seen from Figure 1 that the maximum tensile stress of the artificial pillar appears in the middle area, and the tensile stress zone becomes smaller with the increase of the thickness of the top pillar. Table 3 shows the maximum tensile stress and safety factor under different boundary pillar thickness, it can be found that with the increase of the thickness of the top pillar, the maximum tensile stress of the boundary column becomes smaller and the safety factor increases.

Tab.5 - The maximum stress of different boundary pillar thickness when the span is 7 m

Thickness of boundary pillar / m	Maximum tensile stress / Mpa	Safety factor
3	1.36	1.19
4	1.04	1.56
5	0.98	1.66
6	0.94	1.73
7	0.91	1.79

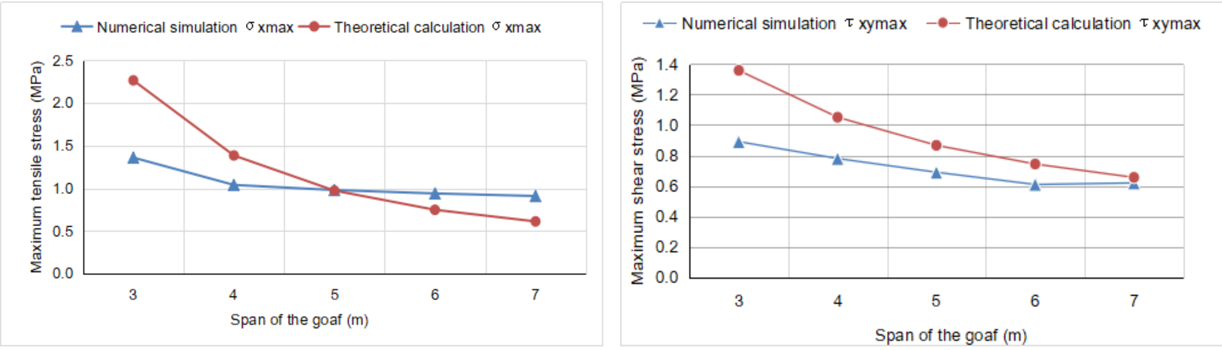
Based on the principle that the safety factor of tensile stress in artificial pillar is not less than 1.2, the minimum boundary pillar thickness is recommended as shown in Table 6.

Tab. 6 - The recommended values of different boundary pillar thickness from numerical simulation

The span of the goaf / m	6	8	10	12	22
Thickness of artificial pillar / m	2.2	3.2	4.2	5.2	11.2

Comparison between theoretical calculation and numerical simulation results

Figure 12 shows the comparison between theoretical calculation and numerical simulation of artificial pillars with different widths. The research shows that when the width of the artificial pillar is less than 5m, the numerical simulation value of tensile stress is larger than that of the elastic foundation theory. When the width of the artificial pillar is greater than 5m, the result is opposite. The shear stress value calculated by elastic foundation is higher than that of the numerical simulation. This is because the elastic foundation beam theory does not consider the lateral pressure affected by the horizontal sides of the beam, and in the actual project, the slope of the open pit has lateral pressure on the artificial pillar, which will reduce the shear stress.



(a) Maximum tensile stress *(b) Shear stress*

Fig.12 - Comparison between theoretical calculation and numerical simulation results

CONCLUSION

A new multi-function type of artificial boundary pillar scheme of reinforced concrete is proposed in this paper, which creates favourable conditions for underground mining below the pillar and stacking tailings over the pillar. Based on a variety of theoretical methods and numerical simulation techniques, the stability of artificial pillars with different structure sizes is analysed, which provides a reference for mine safety mining and actual production.

In this paper, the mechanical model of the artificial pillar is established, and the numerical simulation of MIDAS-FLAC3D software is used to verify and compare the results. The simulation results show that the thickness of the artificial pillar and the span of the goaf have an important influence on its stability. The maximum tensile stress of the artificial pillar is inversely proportional to its thickness, and it is directly proportional to the width of the goaf.

The multi-functional artificial pillars have good impervious and flood control characteristics and pressure bearing capacity, and can effectively separate the influence of the open pit and the underground that realizes the effective utilization of resources and greatly improve the economic efficiency of mines. At the same time, it enhances the stability of the slope for the piled tailings in the open pit the slope play a supporting role. And it effectively reduces the tailings reservoir area, and has good ecological and environmental value, which can provide an demonstration role for the relevant mines.

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REFERENCES

[1] E. Bakhtavar, K. Shahriar, K. Oraee. Transition from open-pit to underground as a new optimization challenge in mining engineering[J]. Journal of Mining Science, 2009, 45(5):485-494.
[2] E. Bakhtavar. Transition from open-pit to underground in the case of Chah-Gaz iron ore combined mining[J]. Journal of Mining Science, 2013, 49(6):955-966.
[3] E.A Cordova, M.G Nelson. Open pit and underground mine interaction with phase 2[C]. 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, 2010, Salt Lake City, Utah.
[4] Bakhtavar Ezzeddin, Shahriar Kourosh, Oraee Kazem. Mining method selection and optimization of transition from open pit to underground in combined mining[J]. Archives of Mining Sciences, 2009, 54(3):481-493.
[5] Lu Guang-luo, Zhou Quan, Liu Xiao-ming. Safety analysis of interlayer thickness from open pit to underground mining[J]. Journal of Mining and Safety Engineering, 2011, 28(1):132-137.
[6] Zhao Xing-dong, Li Lian-chong, Tang Chun-an. Stability of boundary pillars in transition from open pit to underground mining[J]. Journal of Central South University, 2012,19(11): 3256-3265.
[7] I.V. Sokolov, A.A. Smimov, Yu. G Antipin. Rational design of ore discharge bosom in transition from open pit to underground mining in udachny mine[J]. Journal of Mining Science January, 2013, 49(1): 90-98.
[8] C. Gonzalez-Nicieza, M.I. Alvarez-Fernandez, A. Menendez-Diaz. A comparative analysis of pillar design methods and its application to marble mines[J]. Rock Mechanics and Rock Engineering, 2006, 39(5): 421-444.
[9] Liu Hong, Hu Qian-ring, Wang Jin-an. Analysis on stability of pillar and stiff roof system in the gob area[J]. Journal of Coal Science&Engineering, 2009, 15(2): 206-209.
[10] Bi Jinzhong, Wang Ping, Chen Cong. Study on safety thickness oftop-pillar in transferring from open pit to underground mining[J]. Nonferrous Metals:Mine Section, 2013, 65(4):8-11. (in Chinese)
[11] Shi Jianjun, Meng Haili, Gao Kelin. Numerical simulation of the stability of boundary pillar[J]. Mining and Metallurgical Engineering, 2004, 24(6):7-10. (in Chinese)
[12] Liu Ting-ting, Lu Guo-bin, Tong Li-ming. Numerical simulation study of the influence on stability of slope by underground mining under opencast coal mine slope[J]. Journal of Coal Science&Engineering, 2011, 17(4): 397-400.
[13] Alexander Vyazmensky, D.Stead, D. Elmo. Numerical analysis of block caving-induced instability in large open pit slopes:A finite element / discrete element approach[J]. Rock Mechanics and Rock Engineering, 2010, 43(1): 21-39.
[14] A.Mortazavi, EP. Hassani, M. Shabani. A numerical investigation of rock pillar failure mechanism in underground openings[J]. Computers and Geotechnics, 2009, 36: 691-697.
[15] A. Jaiswal, B.K. Shrivastva. Numerical simulation of coal pillar strength[J]. International Journal of Rock Mechanics & Mining Sciences, 2009, 46: 779-788.