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# Energy method and numerical simulation of critical backfill height in non-pillar continuous mining①

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**Abstract**: Non-pillar continuous mining(NPCM) is regarded as a high-efficient, high-level and one-step mining technology, which can be divided into two substopes. Backfill stability status in substope Ⅰ, which directly influence the loss rate and dilution rate, etc, will determine whether the experimental research is successful or not. By employing energy method of limit analysis and finite element numerical simulation method, the critical backfill height was determined under the prerequisite condition of its stability, which put forward theoretical basis for reasonable and correct selection of backfill's parameters. The result showed that the first backfill could not keep stable for NPCM, while the other was able to.

**Key words**: continuous mining; critical height; energy method; numerical simulation
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## 1 INTRODUCTION

Backfilling is being used increasingly in underground mines as a support medium in/around mining areas. The mining method known as cut-and-fill stoping, which incorporates backfilling in its operational cycle, is ranked as a major method of underground mining. Even room-and-pillar mining and sublevel stoping methods also employ backfill so that the remnant pillars can be recovered after the primary mining operations have been completed. As a general rule, backfill performs the following unique functions[1]:

(1) Serves as ground control—wall support and stope stabilization;

(2) Provids a working floor—artificial roof in underground cut-and-fill stoping;

(3) Fills voids;

(4) Disposes of waste rock and/or tailings;

(5) Serves as subsidence and fire control, rock-burst control etc.

Obviously, the correct design and selection of backfill are prerequisite, important, and necessary for these benefits to be obtained effectively. An increasing understanding of the support characteristics of backfilling in rock support, and of the interaction between the rockmass and the backfill, could lead to optimized designs for backfilling. Many scholars employed analytical (often empirical) formula to calculate strength or height of backfill[2,3]. For example, Huang[2] used the following formula to calculate the self-standing height of backfill:

$$H = \frac{1}{\gamma}\left(\frac{2C\cos\Phi}{1-\sin\Phi} - p_0\right) \qquad (1)$$

where $H$ is self-standing height of backfill, $\gamma$ is unit mass of backfill, $C$ is cohesion of backfill, $\Phi$ is friction angle of backfill and $p_0$ is hanging-wall's pressure on backfill.

On the other hand, the numerical methods, especially the finite element method, were applied to investigate the performance of backfill[1,4~7]. It is announced that the numerical methods have a wide scope of application, and so are highly appreciated by many scholars. The present paper employs both energy method and numerical method to evaluate the critical height of stable backfill, and then to provide a new

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methodology to assist with the design and selection of backfill.

## 2 BRIEF INTRODUCTION AND KEY TECHNIQUE OF NPCM

Since 1980's, with the development of high efficient equipment of stoping, mucking and transporting, and the development of bulk mining technology, there is a tendency for mining method to become high-level, continuous, and one-step. Continuous mining system can be divided into three groups: continuous stope system, continuous level system, and continuous mine system. In mine's production system, stope is the basic unit, strengthening and balancing stope production process is the basis for raising mine's gross production capacity. Consequently, as for a metal mine's production system, continuous stope mining system is the first to be considered. During past two decades, Mining Institute of CSUT has finished some research and experiments on realizing continuous stope mining system and enormously enhance mine's production. On this basis, continuous level mining system research was put forward and carried out in a copper mine. Completion of this research will play a great role not only in the development of copper mine's technology, but also in enhancement of experimental mine's production, and in the advancement of underground mining technology as well.

### 2.1 Experimental mine geology and mining condition

The experimental stopes are located in the second( Ⅱ ) main ore body, which is 45 m in ore strike length, average 10 m thick, dip angle 75° ~85°. The ore is metamorphic copper bearing magnetite, $f=16\sim26$, hanging wall is granite, $f=6\sim8$, foot wall is $f=8\sim12$. Level height is 60 m( $-360\sim-300$ m), the total ore is 117000 t, average grade is 0.93%. Physical and mechanical properties of rocks and fills are listed in Table 1.

### 2.2 Brief introduction and key technique of NPCM

Non-pillar continuous stoping scheme is described as that ore body in one level is divided into stope areas, stope areas into stope units. No pillars were left among these stope units. Deep-hole powerful open-stoping procedure is employed, following by fast backfilling: the opening-out, stoping and backfilling processes are carried out separately in adjacent mining units, while linked up with each other, which compose of continuous mining. Industrial experimental mining unit stoping patten of NPCM is shown in Fig. 1.

From Fig. 1, the $i$th mining unit was divided into substope Ⅰ and substope Ⅱ, moreover, a temporary wall-pillar, with length of 5~6 m, was kept between the two substopes in this mining unit. Mining sequences were that: firstly, ore in substope Ⅰ was extracted, then backfilled with cemented-tailings to form artificial partition; secondly, ore body in substope Ⅱ was extracted, of course, the temporary wall-pillar is cut just at the end of extraction; thirdly, after the extracted ore in substope Ⅱ was mucked by using of vibration mucking machines, pure tail-

**Table 1** Physical and mechanical properties of rocks and fill

| Rock/Fills | UCS*, $\sigma_c$/MPa | Tensile strength, $\sigma_t$/MPa | Elastic modulus, $E$/MPa | Poisson's ratio, $\gamma$ | Cohesion, $C$ /MPa | Friction angle, $\Phi$/(°) | Body force, $w$/(t·m$^{-3}$) |
|---|---|---|---|---|---|---|---|
| Granodiorite | 74.00 | 1.80 | 18000 | 0.16 | 1.50 | 53 | 2.80 |
| Marble | 63.30 | 3.30 | 63000 | 0.26 | 10.80 | 50 | 2.80 |
| Magnetite(bearing Cu) | 203.40 | 9.50 | 95000 | 0.31 | 21.50 | 51 | 4.04 |
| Garnet(bearing Cu) | 199.30 | 8.70 | 93000 | 0.23 | 13.20 | 50 | 3.28 |
| Backfills | 2.40 | 0.42 | 300 | 0.16 | 0.28 | 38 | 2.10 |
| | 3.50 | 0.50 | 979 | 0.30 | 0.66 | 35 | 2.21 |

* Uniaxial compressive strength

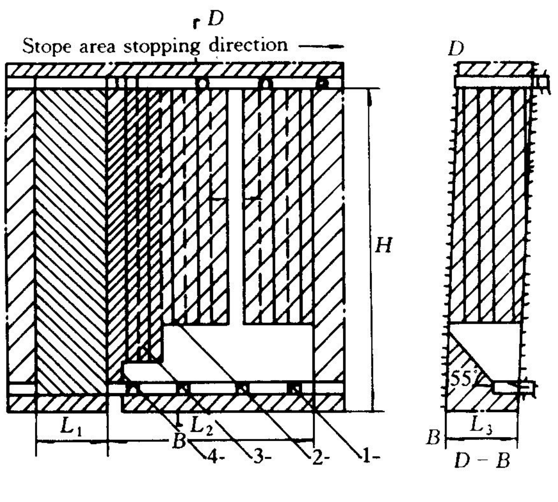


**Fig.1** Experimental mining unit stoping pattern of NPCM

1—Horizontal vibration mucking base struction; 2—$d$165 mm vertical deep hole; 3—Temporary wall-pillar; 4—Backfill; $L_1$—Length of substope Ⅰ; $L_2$—Length of substope Ⅱ; $L_3$—Orebody thickness; $H$—Level height

ings were applied to fill the whole substope Ⅱ.

The stability of artificial partition (e.g. backfill in substope Ⅰ) and temporary wall-pillar plays a critical role in controlling ore dilution rate and roof weighting problem: smooth vertical temporary wall-pillar creates favorable conditions for backfilling in substope Ⅱ, and protect the backfill from collapsing during substope Ⅱ bulk extraction. Obviously, during the late period of extraction and mucking, backfill's exposure surface was so high and so large that there is an increasing tendency to collapse. Consequently, extraction fraction and dilution rate depend largely on the stability of backfill. The correct selection of backfill will determine whether backfill is stable or not. That is the key techique of NPCM.

## 3 ENERGY METHOD

Underground cut-and-fill mining method, with high level and high efficiency, often involves stability problem of backfill with a large exposure vertical surface. Research on such stability problems intrigue a lot of scholars from home and abroad. Energy method in limit value analysis and three dimensional finite element numerical simulation were employed to determine the backfill's critical height in NPCM. Reasonable selection of backfill's parameters was based on these analyses.

As mentioned above, backfill in substope Ⅰ was submitted to be exposed laterally and vertically. Because the drill gallery above the substope Ⅰ is not backfilled(the drill gallery is left for the space for up-stoping in the next upper level), backfill in substope Ⅰ may be modeled as vertical slope showed in Fig.2 (supposed to be unit thick). If the backfill is supposed to be tensionless and non-support vertical backfill is going to collapse only under gravity, then the height is called critical height. It is a common sense that under the load of gravity, there is a tendency for vertical backfills to slide downwards, so tension crack is formed at the shoulder of backfills. The crack's depth is supposed to be $nH(0<n<1)$, the included angle between slide face and vertical line is $\beta$, and that between the velocity vector ($v$) and slide face is $\Phi$, which is also the medium(backfill) inner friction angle[8]. From Fig. 2, the vertical component of velocity vector is as expressed $v\cos(\beta+\Phi)$, and the slide body's weight is $\frac{1}{2}wH^2\mathrm{tg}\beta(1-n^2)$, where $w$ is backfill's unit body force, $H$ is height of backfill. $ABDE$ is the backfill in critical state, $AE$ is the supposed tension crack.

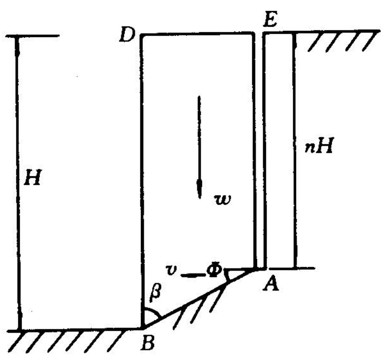


**Fig.2** Critical model of backfill in substope Ⅰ

The weight power of slide body is obtained as:

$$\frac{1}{2}wH^2\mathrm{tg}\beta(1-n^2)\cdot v\cos(\beta+\Phi)$$

The length of slide face is $H(1-n)/\cos\beta$, then the dissipation power on intermittent velocity face may be calculated as:

$CH(1-QDn)v\cos\Phi/\cos\beta$

According to conservation principle of energy, weight power is equal to inner dissipation power, that is expressed by

$$\frac{1}{2}wH^2\mathrm{tg}\,\beta(1-n^2)\cdot v\cos(\beta+\Phi)=\frac{CH(1-n)v\cos\Phi}{\cos\beta} \quad (2)$$

When the variable $H$ has been calculated, $\partial H/\partial\beta=0$, $n\rightarrow 1$ (because backfill is supposed to be tensionless). Consequently, the upper limit of the critical backfill height may be determined by

$$H_{cr}^{+}=\frac{2C}{w}\mathrm{tg}(\pi/4+\Phi/2) \quad (3)$$

Similarly, the lower limit of critical backfill height may be obtained as follows:

The balance equation was expressed as

$$\frac{\frac{1}{2}wH\cos\Phi-C}{\mathrm{tg}\,\Phi}+\frac{1}{2}wH\sin\Phi=\frac{1}{2}wH \quad (4)$$

Transform Eqn. (4) to

$$\frac{1}{2}wH=C\cos\Phi+\frac{1}{2}wH\sin\Phi \quad (5)$$

Then the critical height lower limit is

$$H_{cr}^{-}=\frac{2C}{w}\mathrm{tg}(\pi/4+\Phi/2) \quad (6)$$

According to Eqns. (3) and (6), $H_{cr}^{+}=H_{cr}^{-}$. The critical height of tensionless backfill with vertical slope may be obtained by

$$H_{cr}=\frac{2C}{w}\mathrm{tg}(\pi/4+\Phi/2) \quad (7)$$

Substituting the first backfill's parameters in Table 1 (e.g. $C$, $\Phi$ and $w$), the critical height is 54.67 m. It is obvious that the first backfill is unstable if filled into the test mining unit with a height of 60 m. However, the second backfill is considered to stable.

## 4 NUMERICAL SIMULATION METHOD

### 4.1 Numerical modeling

A three-dimensional elastoplastic finite element program, which was developed by the authors to simulate dynamic process in mining engineering such as multistage excavation, backfilling, caving, and construction etc, was selected for the numerical modeling investigation[6,7]. Based on the preliminary estimation of excavation influence area, whose size is 3 ~ 5 times of the size of mining stope, numerical model was set up to represent NPCM experimental mining unit, shown in Fig. 3. The Drucker-Prager yield criterion was employed to model all the materials. Physical and mechanical parameters, listed in Fig. 1, were reevaluated according to Hoek-Brown empirical formula in order to obtain input values in the NPCM model, which in some extent represent the in-situ rock mass characters. Boundary condition was normal displacement restrained in front, back, left, right, and lower surface of the model, while free in upper surface to simulate displacement of earth's surface. Few controlling coordinates and necessary parameters are needed to be put into the program data file to auto-generate finite element topology and mesh. There is no need to consider tectonic stress field of strata according to the conclusion of in-situ investigation. Nine step simulations were incorporated in accordance with actual excavation and backfilling process. The first step is carried out only in gravity in-situ stresses.

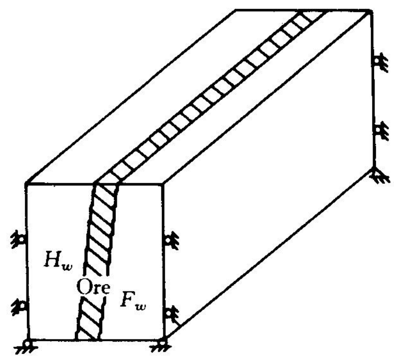


**Fig.3** Simplified 3-D model of orebody

### 4.2 Numerical results and analysis

Stress, strain and displacement, in surrounding walls and backfills at every excavation and backfilling step, are able to be obtained through finite element simulation. Analysis of the mining dynamic effect has to be based on these numerical results. A few useful and necessary results are listed here and most are neglected. Front horizontal displacement of backfill along strike section in substope Ⅰ was listed in Fig.4(Nodes from 673 to 679).

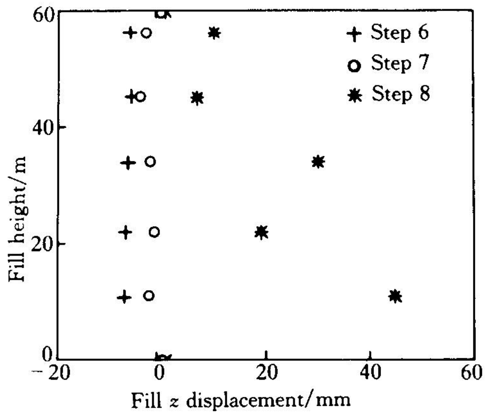


**Fig.4** Front horizontal displacement of backfill

According to backfill's stress, at step 6 and 7, backfill elements were all in elastic state probably because the temporary wall-pillar has not been excavated. However, at step 8, backfill was exposed with large areas, its maximum tension stress is 0.648 8 MPa, larger than the tension stress. Maximum shear stress is 0.595 1 MPa, and all the backfill elements have yielded, in which the maximum plastic strain element 340 gets to $3\,371\times10^{-6}$. Obviously, the first backfill is not stable. As for the second backfill, maximum plastic strain in element 340, is $2\,891\times10^{-6}$, and the maximum tension stress is only 0.344 MPa. Just from the stress state, the second backfill is also stable.

## 5 CONCLUSION

By using energy method in limit analysis and three dimensional finite element numerical simulation to determine the critical height of substope Ⅰ under the condition of stability, theoretical basis for reasonable selection of backfill's parameters has been put forward. Energy method only provides a preliminary estimation, however, numerical simulation and analysis are detailed and comprehensive. The result shows that the first backfill may not keep stable for NPCM, while the other can do. The influence of explosive dynamic load has not been considered in this paper, which is also an interesting research program.

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