Wear mechanism and serious wear position of casing pipe in vertical backfill drill-hole

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Abstract: Vertical backfill drill-hole is usually a key project in an underground mine with backfill method and can be easily damaged by impact of backfill slurry. Observation of the damaged vertical backfill drill-holes in Jinchuan Nonferrous Metal Corporation (JNMC), Gansu Province, China, given by a digital drill-hole video camera, indicated that there usually exist serious wear zones in casing pipe in vertical backfill drill-hole (CVBH). It was suggested that serious wear position of CVBH should be located at an interface between air and solid−liquid mixture within CVBH. Backfill slurry falls freely and impacts the wall of CVBH near the interface with great momentum and energy coming from high speed free fall of backfill slurry. The depth of serious wear position of CVBH, i.e., free fall height of backfill slurry in CVBH, can be estimated by the height of vertical backfill drill-hole, the length of horizontal pipeline, the density of slurry and the hydraulic gradient of pipeline system. A case study indicated that the estimation equation of serious damage depth of CVBH was of enough accuracy and was helpful for daily maintenance and management of vertical backfill drill-hole.

Key words: vertical backfill drill-hole; backfill pipeline; impact; wear mechanism; serious wear position

1 Introduction

Backfill method is one of the most important mining techniques in underground mines due to high recovery rate of mineral resources and qualified safety control [1]. Binding material, aggregate and water are mixed and usually transported through casing pipe in vertical backfill drill-hole (shortly, CVBH) and horizontal or inclined pipeline into stope by gravity flow. Pressure from slurry weight in CVBH is the reason of slurry movement in this transportation system [2−4]. Vertical backfill drill-hole, obviously, plays the most important role in the transportation of backfill slurry from surface to underground stope [5−6], and is easily damaged by erosion and abrasion of the slurry. Mining cycles may be disrupted once CVBH is broken.

It is very common for inspection and repair of pipeline in municipal transportation system of natural gas, oil and water. The most common method is to reveal broken pipeline and then to carry out inspection and repair process [7]. Repair techniques include welding, sealing, pressure reducing, partial replacement, paint spraying and tube lining [8−11]. Inspection and maintenance of damaged CVBH are, however, more difficult because the damage condition of CVBH is influenced by many factors and cannot be easily observed. It is known that the influencing factors on the abrasion of CVBH include features of backfill slurry, drilling quality of the hole, size, materials and installation quality of pipeline in the hole, and ratio of total length to vertical height of pipeline [12−13], but the abrasion mechanism of CVBH is still not clear because many influencing factors can not be quantitatively determined. Wear types of CVBH are clarified in this work, based on the investigation of damaged CVBH in Jinchuan Nonferrous Metal Corporation (JNMC), Gansu Province, China, and on the analysis of flow regime of backfill slurry in CVBH. The physical transportation model of backfill slurry is set up and the wear mechanism of backfill pipeline in drill-hole is discussed based on the change of backfill slurry's momentum and energy. In addition, an estimation approach of the most serious wear position of backfill hole is suggested.

2 Flow regime of backfill slurry and wear pattern of CVBH

2.1 Flow regime of backfill slurry

Static head of backfill slurry in vertical hole is the motive power of slurry flow in gravity transportation system. Assuming that the inner diameter of backfill hole is fixed and that the vertical height of the hole, the length of horizontal pipeline, the density of slurry, the hydraulic gradient of transportation system are respectively H, L, γ_j and i, the backfill slurry is transported at one of the following three patterns:

1) Static head is less than the resistance to flow of backfill slurry and slurry cannot be transported while $\gamma_j H < i(H+L)$;

2) Static head is equal to the resistance to flow of backfill slurry and slurry fills the total vertical pipe while $\gamma_j H = i(H+L)$;

3) Static head is greater than resistance to flow of backfill slurry and slurry freely falls in upper part of backfill hole while $\gamma_j H > i(H+L)$.

It is a common case in backfill system that backfill slurry in vertical hole initially falls to interface between air in upper part of the hole (H_1) and solid-liquid mixture in lower part of the hole (H_2), as shown in Fig. 1 [14]. In other words, backfill slurry in vertical hole usually flows in two regimes, free fall movement and smooth flow movement.
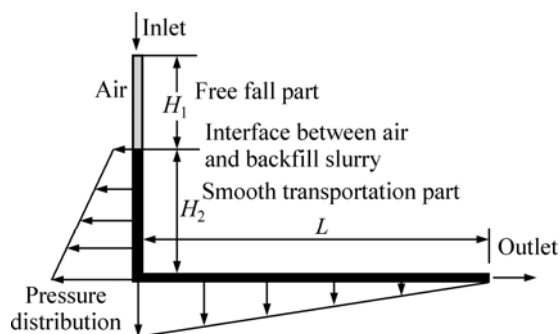

Fig. 1 Common sketch of backfill transportation system

2.2 Wear pattern of CVBH

Backfill drill-holes in Loushou Mine of JNMC were detected by using digital drill-hole video camera, and it was found that there usually exists a special range where CVBH is seriously damaged as shown in Table 1. For example, serious wear depths of holes No.W2 and No.E5 in JNMC are 27−31 m and 10−15 m below the surface, respectively. Partially serious wear is caused by impacting of backfill slurry in free fall part of CVBH to partial pipe wall at a high speed. Wear of pipe wall is greatly lessened in smooth transportation part of CVBH because slurry flows at a stable velocity in this area.

Table 1 Serious wear depth of damaged backfill holes in JNMC given by digital drill-hole video camera

Hole No.	Depth/m	Inner diameter/mm	Serious wear depth/m
W1	84.55	152	24−30
W2	84.55	152	27−31
W3	132	152	60−65
W4	84	152	18−25
E1	274	159	106−120
E2	120	100	60−65
E3	120	100	63−65
E4	120	100	61−65
E5	60	100	10−15
E6	60	100	18−25

3 Wear mechanism of CVBH

The analysis mentioned above suggests that impact of backfill slurry in free fall part of CVBH is the main reason of CVBH damage. The wear mechanism of CVBH can be clarified by changes of backfill slurry's momentum and energy when it flows in CVBH (Fig. 2).
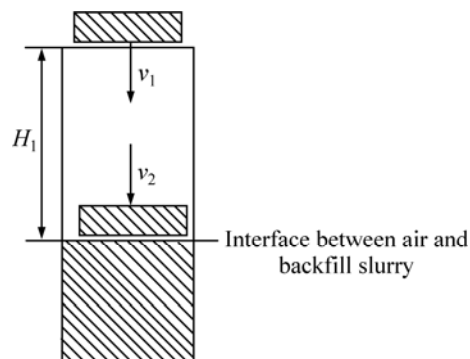

Fig. 2 Impact wear model of backfill slurry in CVBH

3.1 Wear caused by backfill slurry's momentum

The movement of backfill slurry in free fall part of CVBH can be approximately regarded as uniformly accelerated linear motion. According to the characteristics of the motion, the following equations can be educed:

$$H_1 = v_1 t + \frac{1}{2} g t^2 \tag{1}$$

$$v_2 = v_1 + gt \tag{2}$$

where H_1 is the vertical height of the free fall part; v_1 is the initial velocity of backfill slurry in unit mass when it enters into the pipeline; v_2 and t are the velocity of the backfill slurry and time when it arrives at interface between air and backfill slurry; and g is the gravity

acceleration. Then, v_2 can be calculated from Eqs. (1) and (2) as follows:

$$v_2 = c\sqrt{2gH_1 + v_1{}^2} \tag{3}$$

where c is a speed correction coefficient depending on diameter and roughness of the pipe and some other factors. It is usually determined by experiment, varying form 0.7 to 0.8. It can be seen from Eq. (3) that v_2 increases with increasing H_1.

The faster the speed of backfill slurry is, the greater the momentum is. The momentum of backfill slurry reaches a maximum when it drops to the interface between air and backfill slurry, and then reduces almost to zero in a short time because of the collision at the interface. The rapid decrease of momentum produces a huge impact. Assuming that the density of backfill slurry is ρ, the sectional area of pipe is A and the impact time is Δt, the total mass of backfill slurry (Δm) impacting on the interface can be presented as:

$$\Delta m = \rho \cdot v_2 \cdot \Delta t \cdot A \tag{4}$$

and the momentum change (ΔP) of backfill slurry is equal to

$$\Delta P = \Delta m \cdot v_2$$

The impact (F) of slurry to the interface defined as momentum change in unit time can be calculated as:

$$F = \frac{\Delta P}{\Delta t} = \frac{\Delta m \cdot v_2}{\Delta t} \tag{5}$$

Combining Eqs. (4) and (5), F can be shown as:

$$F = a \cdot \rho \cdot v_2^2 \cdot s \tag{6}$$

where a is a correction coefficient, here a=0.7−0.8. Eq. (6) shows that impact F has direct proportion relation to the square of v_2. It can be known that the faster the terminal speed of slurry is, the more serious the impact wear of the pipeline would be. It is necessary, therefore, to reduce the height of free fall part (H_1) in order to lessen wear degree of CVBH.

3.2 Wear caused by backfill slurry's energy

The total energy (E) needed when backfill slurry moves from the pipeline inlet to the interface between air and backfill slurry is the sum of initial kinetic energy of backfill slurry and the work done by gravity. Assuming that the unit mass of backfill slurry entering into pipeline in the unit time (Δt) is Δm, the total energy E can be computed as:

$$E = \frac{1}{2} \cdot \Delta m \cdot v_1{}^2 + \Delta m \cdot g \cdot H_1 \tag{7}$$

Substituting $\Delta m = \rho \cdot Q \cdot \Delta t$ into Eq. (7), Eq. (7)

can be rewritten as:

$$E = \frac{1}{2} \cdot \rho \cdot Q \cdot v_1{}^2 \cdot \Delta t + \rho \cdot Q \cdot g \cdot H_1 \cdot \Delta t \tag{8}$$

where Q is the flux of backfill slurry. The energy (E) of backfill slurry mainly acts on the wall of the pipeline. That is to say, backfill slurry consumes the energy in the process of friction to the pipeline wall. Energy acted on unit surface area of pipe wall (E_w), therefore, can reflect the degree of the pipeline's abrasion. Great E_w means serious wear of CVBH. E_w can be calculated from Eq. (8) as:

$$E_w = (\frac{1}{2} \cdot \rho \cdot Q \cdot v_1{}^2 \cdot \Delta t + \rho \cdot Q \cdot g \cdot H_1 \cdot \Delta t)/S \tag{9}$$

where S denotes the effective abrasion area that slurry contacts with the wall of pipeline. The smaller the effective abrasion area that unit mass slurry contacts the pipeline wall, the more serious the abrasion of the pipeline would be because of the increase of the energy consumption on the unit area. The relation between the deflection rate of drill-hole and the wear of CVBH can be well explained by E_w. For example, E_w is large and wear is serious for CVBH because of lower effective abrasion area while the drill-hole is greatly inclined.

4 Estimation of serious wear position of CVBH

The flow regime of backfill slurry and wear pattern of CVBH suggest that the interface between air and backfill slurry in vertical backfill drill-hole is the weakest area where pipe wall is impacted by backfill slurry at a high speed. Therefore, serious wear position of CVBH can be estimated by the computation of interface depth. Interface depth, H_2 in Fig. 1, can be calculated according to the following equation:

$$H_2 = i_2 L/(\gamma_j - i_1) \tag{10}$$

where γ_j is the density of backfill slurry; i_1 and i_2 are the hydraulic gradient of backfill slurry in both vertical and horizontal pipelines; L is the length of horizontal pipe. The depth of easy damaged position, H_1, can be estimated from Eq. (10) as follows:

$$H_1 = H - H_2 = H - i_2 L/(\gamma_j - i_1) \tag{11}$$

where H denotes the height of vertical backfill drill-hole. The hydraulic gradient of backfill slurry in both vertical and horizontal pipelines are usually only unknown variables in Eq. (11). The hydraulic gradient of backfill slurry relates to many factors [15−16] and can be calculated by [17]:

$$i = i_0 \left\{ 1 + 108 C_v^{3.96} \left[\frac{gD(\gamma_j - 1)}{v^2 \sqrt{C_x}} \right]^{1.12} \right\} \tag{12}$$

where C_v is the volume fraction of backfill slurry; D is the inner diameter of pipe; i_0 is the hydraulic gradient of fresh water; C_x is the settlement resistance factor of solid particles; v is the speed of backfill slurry. The speed of backfill slurry can be computed according to the flux of backfill slurry (Q) and the inner diameter of pipe (D) as follows:

$$v = \frac{4Q}{\pi D^2} \tag{13}$$

The following equation can be used to approximate i_0:

$$i_0 = \lambda \frac{v^2}{2gD} \tag{14}$$

where λ is the friction resistance factor estimated as:

$$\lambda = \frac{K_1 \cdot K_2}{\left(2 \lg \dfrac{D}{0.00024} + 1.74 \right)^2} \tag{15}$$

where K_1 and K_2 are the installation and joint quality factors of the pipeline, respectively, each taken as 1.1 here.

The settlement resistance factor of solid particles (C_x) can be calculated as:

$$C_x = \frac{1308(\gamma_j - 1)d_{cp}}{\omega^2} \tag{16}$$

where d_{cp} is the average size of the mixture; ω is the average settlement rate of solid particles which can be calculated according to the temporary parameter $A = \sqrt[3]{0.0001/(\gamma_j - 1)}$.

When $d_{cp} < 0.3A$,

$$\omega = 5450 d_{cp}^2 (\gamma_j - 1) \tag{17}$$

when $0.3A \leq d_{cp} < A$,

$$\omega = 123.04 d_{cp}^{1.1} (\gamma_j - 1)^{0.7} \tag{18}$$

when $A \leq d_{cp} < 4.5A$,

$$\omega = 102.71 d_{cp} (\gamma_j - 1)^{0.7} \tag{19}$$

and when $d_{cp} \geq 4.5A$,

$$\omega = 51.1 \sqrt{d_{cp}(\gamma_j - 1)} \tag{20}$$

5 Case study

JNMC, a worldwide famous nickel-copper producer in China, uses downward cut and fill method to extract its weak deposit. Backfill slurry formed by water and a mixture of portland cement and milled gobi sand with mass ratio of 1:4 is transported into underground stope by gravity through a combination of vertical backfill hole and horizontal pipeline. The designed flow capacity is 100 m^3/h. The volume fraction (C_v) and density (γ_j) of backfill slurry are 56.6% and 1.98 t/m^3, respectively. The average size of the mixture (d_{cp}) of cement and gobi sand is 0.079 cm. Since $A = \sqrt[3]{0.0001/(\gamma_j - 1)} = 0.047$, $d_{cp} = 0.079$ is greater than A but less than $4.5A$. The average settlement rate of solid particles (ω) can be estimated by Eq. (19) as follows: $\omega = 102.71 d_{cp} \cdot (\gamma_j - 1)^{0.7} = 8$ cm/s, and consequently $C_x = 1.582$ can be calculated from Eq. (16). Substituting the parameters mentioned above, the hydraulic gradients of pipes with different diameters can be given by Eq. (12). Serious wear depths (H_1) of damaged CVBH in JNMC mentioned in Table 1 can be estimated easily by Eq. (11) as shown in Table 2, because the height of backfill hole, the length of horizontal pipeline, the density of slurry and the hydraulic gradients of both vertical and horizontal pipelines have been known. It can be found that the estimated serious wear depths of damaged CVBH are similar with the survey results by digital drill-hole video camera, based on the comparison of Tables 1 and 2.

Table 2 Estimated wear depth of damaged CVBH in JNMC

Hole No.	H/m	L/m	D_1/mm	D_2/mm	v_1/(m·s^{-1})	v_2/(m·s^{-1})	i_1	i_2	H_1/m
W1	88	425	152	100	1.685	3.892	0.1105	0.2683	27.01
W2	88	425	152	100	1.685	3.892	0.1105	0.2683	27.01
W3	132	468	152	100	1.685	3.892	0.1105	0.2683	64.85
W4	84	414	152	100	1.685	3.892	0.1105	0.2683	24.60
E1	274	1092	159	100	1.540	3.892	0.1074	0.2683	117.32
E2	120	366	100	100	3.892	3.892	0.2683	0.2683	62.24
E3	120	366	100	100	3.892	3.892	0.2683	0.2683	62.24
E4	120	366	100	100	3.892	3.892	0.2683	0.2683	62.24
E5	60	288	100	100	3.892	3.892	0.2683	0.2683	11.39
E6	60	252	100	100	3.892	3.892	0.2683	0.2683	20.46

H and L denote the height of CVBH and length of horizontal pipe to stope; D_1 and D_2 are the diameter of both vertical and horizontal pipe; v_1 and v_2 are the speed of backfill slurry in both vertical and horizontal pipe given by Eq. (13); i_1 and i_2 are hydraulic gradients of both vertical and horizontal pipelines estimated by Eq. (11), respectively

6 Conclusions

1) Observation of digital drill-hole video camera indicated that the wear condition of casing pipe of vertical backfill drill-hole (CVBH) was not the same along whole depth direction. There usually existed a serious wear zone for each CVBH.

2) It is a common case that backfill slurry falls freely in CVBH until it reaches an interface between air in upper part of the hole and solid−liquid mixture in lower part of the hole, and then flows smoothly. Impact from free fall of backfill slurry is the primary damage pattern of CVBH.

3) The terminal speed that backfill slurry arrives at the interface increases with increasing the vertical height of free fall part in CVBH. The wear degree of CVBH depends on momentum and energy of backfill slurry in CVBH which have close relation to the terminal speed of backfill slurry. Generally speaking, the faster the backfill slurry falls in CVBH is, the greater the momentum and energy consumption acting on the wall of CVBH are and the more serious the damage of CVBH would be.

4) Serious wear position of CVBH lies in interface between air and backfill slurry. Serious wear depth of CVBH can be estimated by energy balance principle. Preventive measures can be, therefore, taken in order to avoid serious local wear of vertical backfill hole and to prolong backfill hole's service life.

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充填钻孔内管道磨损机理及易破损位置的确定

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摘　要：充填钻孔是充填法矿山的关键工程之一，容易受到充填料浆的冲击而造成破损。金川公司数字化钻孔电视观测结果表明，充填钻孔存在一个严重破损区域，该区域位于充填钻孔内空气和料浆的接触面上。充填料浆自由降落，具有较高的末期下落速度，而以较高的动量和冲量冲击充填钻孔的内套管管壁。因此，充填钻孔的严重磨损深度，即空气与料浆的接触面高度，可以根据充填钻孔的高度、水平管道的长度、浆体的密度和水力坡度进行估算。实例研究结果表明，该估算方法具有足够的精度，有利于充填钻孔的日常管理和维护。

关键词：充填钻孔；充填管道；冲击；磨损机理；易破损位置

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