Effect of Cross-Sectional Shapes of Vertical Ore Passes on Ore Pass Hang-ups by 3D-DEM

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Abstract

In this study, the geometrical effects of vertical ore passes contributing to ore pass hang-ups were simulated by 3D discrete element method (3D-DEM). DEM is a method of calculating the movement of each discrete element in an analytical region and is suitable for simulating the movement of ore in an ore pass. Here, two types of cross-sectional shapes of vertical ore passes are assumed: circular and square. These ore passes are initially filled with discrete elements, and the ores are then extracted from the bottoms of the vertical passes. In our analysis, the conditions which cause ore pass hang-ups were evaluated, and the effect of the cross-sectional shapes and the possibility of the ore pass hang-ups were discussed. Results showed that cohesion exerted a strong influence on the occurrence of hang-ups. Moreover, the conditions under which hang-ups consistently occur were determined. In addition, the results showed that the hang-up conditions of circular ore passes were more severe than those of square ore passes and that square ore passes were preferable for avoiding hang-ups.

Keywords: Ore, Hang-up, Vertical Ore Pass, 3D-DEM

1. Introduction

More than 200 limestone mines are operative in Japan, most of which are located on mountainsides (Limestone Associate of Japan website). Therefore, vertical ore passes are commonly used to transport ore to industrial sites and shipping sites (Fig.1), meaning ore pass hang-ups are a serious problem (Hadjigeorgiou, 2007), and can cause extensive damage during mining operations. Thus, effective methods and designs to avoid from ore pass hang-ups are crucial. In general, circular cross-sections of vertical ore passes are widely used; however, other cross-sectional shapes have recently been introduced. Nevertheless, the degree to which ore pass hang-ups can be avoided remains unknown.

In order to investigate the mechanism of this phenomenon, Sato and Obara (2014, 2015) conducted numerical simulations by 2-dimensional discrete element method (DEM), which is a method for calculating the movement of each discrete element in an analytical region and it is suitable for simulating the movement of ore in ore passes. In that study, the cohesion between ores and ore pass walls was revealed to be the dominant factor in causing ore pass hang-ups in vertical ore passes. However, these analyses were conducted using 2-dimensional model. Thus, the effect cross-sectional shape was not considered.

In this study, the geometric effects of vertical ore passes on ore pass hang-ups were simulated by 3D-DEM analysis. Here, two types of cross-sectional shapes of vertical ore passes were assumed: circular and square. These ore passes were initially filled with discrete elements, which were then extracted from the bottom of the vertical ore passes. It has already been confirmed that the cohesion and friction coefficient are the main causal factors of ore pass hang-ups (Sato and Obara, 2014 & 2015). In study, and the effect of the cross-sectional shapes and the possibility of the ore pass hang-ups are discussed. Finally, several methods to solve this problem are proposed.
2. 3D-DEM analysis

PFC3D, which is produced by Itasca Consulting Group Inc., was used as the DEM analysis software. During the 3D-DEM analysis, discontinuous sphere particles were generated. The individual movement of each particle was calculated using the forward difference method. As the movement of each ore was similar, this was a suitable method for simulating the movement of ores in the vertical ore pass. Although several parameters were available in the DEM analysis, the friction coefficient and cohesion between particles are thought to be main causal factors of ore pass hang-ups. Thus, the influences of these factors on ore pass hang-ups are the main focus of this study.

2.1 Vertical ore pass model

The influence of the cross-sectional shapes of vertical ore passes are also analyzed in this study. In general, circular cross sections of vertical ore passes are widely used in Japanese mines. In order to discuss other possibilities for avoiding ore hang-ups, simulations of ore flows in square cross sections of vertical ore passes were conducted in this study. The geometric features of circular and square vertical ore pass models are shown in Fig. 2. Here, the diameters of circular ore passes were set to \( D = 6\text{–}10 \text{ m} \). To compare the effect of cross-sectional shapes of vertical ore passes, simulations were conducted by using models with the same cross-sectional area for circular and square ore passes. In the case of square ore passes, the length of side \( L \) was taken as the cross-sectional area equal to those of the corresponding circular ore passes. For example, when the diameter of circular ore passes is \( D = 8 \text{ m} \), the corresponding length of the side \( L \) becomes \( 7.09 \text{ m} \). For the height of vertical ore passes, the value \( H = 400 \text{ m} \) was used.

2.2 Ore size distribution

The sizes and diameter distributions of ores after blasting are mainly influenced by the diameter of the drilling holes used to set explosives and their intervals. In Japan, \( \phi 120 \text{ mm} \) drilling holes are the most widely-used type. In this study, ore size distribution was estimated from digital photo images using Split-Desktop software. An example of fragmentation after blasting is shown in Fig. 3. Ore size was evaluated by comparing the size of the balls in the figure with the ores. Furthermore, ore size distribution obeyed Gaussian distribution. For the values of mean diameter \( d_m = 0.7 \text{ m} \) and standard deviation \( \sigma = 0.05 \text{ m} \) were used in this study.

2.3 Procedures of analysis

The DEM analysis began from the generation of particles in a vertical ore pass. Following this, parameters such as cohesion and the friction coefficients between particles and between particles and ore pass walls were applied to the model. Particles were randomly generated in the analytical regions, and had fallen to the bottom of the vertical ore passes (Fig. 4). This process was continued until all forces acting between particles were balanced. The balanced condition was set to be an initial condition. Next,
the carry-out exit, which was located at the bottom of the ore passes, was opened (Fig.4), thereby initiating the flow out analysis of the particles. If all particles flowed out from the ore pass, it is determined as no hung-up condition. If hang-ups occurred during the flow out process, it is determined as hung-up condition.

As mentioned above, cohesions and friction coefficients are the main causal factors of hang-ups in ore passes. Thus, these analyses were conducted under various combinations of cohesions and friction coefficients. Owing to the characteristics of limestone mines, the rock types of ore pass walls and ores themselves are identical. Other parameters necessary for the DEM analysis were as follows: gravity acceleration $g = 9.81 \text{ m/s}^2$ and particle density $\rho_p = 2,700 \text{ kg/m}^3$.

3. Results

An example of a hang-up is shown in Fig.5. For both circular and square ore passes, the wall surface was smooth although walls have certain values of cohesion and friction coefficients. However, hang-ups occurred mainly 15 m above the carry-out exit. Here, ores formed arches, which supported the additional ores above.

Simulations were conducted for various combinations of cohesions and friction conditions. The hang-up conditions and non-hang-up conditions are shown in Fig.6. The friction coefficient was used as the vertical axis and cohesion as the horizontal axis. Furthermore, hang-ups are plotted as ■ and non-hang-ups are plotted as ● in Figs. 6 (a) and (b), which show the results for circular and square ore passes, respectively. The diameters of the circular ore pass and corresponding square ore passes were 8m. In both cases, there were clear borders between hang-up and non-hang-up conditions. This is indicated by the green line in the figures. As these figures show, when cohesion exceeded a certain value, hang-ups occurred. On the other hand, hang-ups did not occur under certain values of cohesion. When comparing the circular and square ore passes, it is clear that the hang-up region of the square ore pass (the right-hand side of the border in each figure), became smaller than that of the circular ore pass. Thus, square ore pass is preferable for avoiding from hung-up.

In this study, only the representative results are shown. However, the authors analyzed the influence of other factors (different diameters, initial amount of ores in the ore pass, inclination of ore passes, etc.), the results of which will be introduced in the presentation.

4. Conclusions

Ore flows in vertical ore passes were simulated using 3D-DEM analysis and the effects of the cross-sectional shapes of ore passes. Furthermore, simulations were conducted under different cohesion and
friction coefficient conditions. Even in ore passes with smooth surfaces, hang-ups were successfully simulated, and results showed that cohesion exerted a strong influence on the occurrence of hang-up. In addition, the conditions under which hang-ups consistently occur were accurately determined. Finally, it was verified that the hang-up regions of square ore passes were smaller than those of circular ore passes, and that the square ore pass were more preferable for avoiding hang-ups.

![Friction Coefficient vs Cohesion](chart.png)

(a) Circular ore pass

![Friction Coefficient vs Cohesion](chart.png)

(b) Square ore pass

Fig. 6 Hang-up and flow-out map (corresponding diameter 8 m)

References


