STUDY ON FRAGMENTED ROCKS INDUCED BY BENCH BLASTING AND THEIR FLIGHT CHARACTERISTICS IN OPEN PIT MINE

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論文題名：STUDY ON FRAGMENTED ROCKS INDUCED BY BENCH BLASTING AND THEIR FLIGHT CHARACTERISTICS IN OPEN PIT MINE (露天掘り鉱山におけるベンチ発破による起砕岩石とその飛翔特性に関する研究)

区　　分：甲

論　文　内　容　の　要　旨

Rock blasting is the rock excavation and fragmentation technique widely adopted in the various fields of the mining and civil engineering because of its economic efficiency. On the other hand, the blasting operation may have an impact on the surrounding environment, such as ground vibration, flyrock, noise, etc. in case the blasting standard is not appropriate. It is reported that more than 70% of accidents related with the usage of explosive is flyrock. Flyrock may seriously damage buildings and/or human being. Although several prevention methods for flyrock accidents have been proposed, the detailed guideline for the prevention of flyrock has not been developed yet. Moreover, major counter measures for prevention of flyrock have negative influence on the size distribution of fragmented rocks. The size distribution of fragmented rocks effects open pit mining operations such as loading, hauling and crushing, and it may have a large influence of the total operation cost. From these points of view, this study aims to elucidate the rock fracture mechanism induced by bench blasting and the effect of rock mass conditions and blasting designs on flight characteristics and the size distribution of fragmented rocks, and to establish a guideline for safe and efficient bench blasting operation.

Chapter 1 introduces the background of this research including the mining industry in Japan, the accidents related to blasting operation in open pit mine, conventional theory for rock fragmentation by blasting. The problem statements and objectives of the studies, as well as dissertation, are also introduced in this chapter.

Chapter 2 describes the mechanism of rock fragmentation by bench blasting by means of the small-scale experiment. For the quantitative discussion of crack initiation and propagation behavior, the digital image correlation (DIC) method was applied in this experiment. By applying DIC method, the strain of rock mass where cracks initiate and propagate can be visualized and evaluated quantitatively. From the results, it can be found that the initiation of crack is dependent on the strain and a crack initiates and propagates when the strain is over a certain value called as the critical strain. Both the critical strain and the strain rate when a crack initiates increase with increasing the strength of rock mass. It can also be found that the number of cracks induced by blasting increase as the length of burden is shorten. Moreover, the critical strain and the strain rate when a crack initiates also increases with shortening the length of burden. From this result, by shortening the length of burden, not only a rock fragmentation can be improved but also the risk of flyrock is increased because the kinetic energy of fragmented rock is increased. On the other hand, the hole spacing has no obvious impact on the value of critical strain and the number of cracks induced by blasting. However, the spacing between cracks increases with the increasing hole spacing. Therefore, the maximum size of fragmented rocks can be controlled by changing the hole spacing. Based on these results, it can be said that the strain of rock mass is an important parameter to evaluate and predict the initiation and propagation behavior of cracks. Besides, a rock mass strength and the length of burden have obvious impacts on the rock fragmentation and the behavior of fragmented rocks.

Chapter 3 discusses the behaviors of stress waves and crack propagation inside a rock mass in order to discuss the mechanism of rock fragmentation induced by bench blasting by means of ANSYS AUTODYN-3D. The input parameters were determined based on the results of small-scale experiments mentioned in Chapter 2. The results show that the high compressive pressure waves propagate in concentric circles from the blast hole, reflect at the free face and then change into tensile stress waves. Due to the tensile stress waves, tensile failure is generated and stress waves reflect at the free face. After reflected tensile stress waves from two blast holes superpose, the failure zone propagates with the spreading superposed stress waves. Due to the tensile stress waves, tensile failure is generated after reflected tensile stress waves from two blasting holes superpose, and then the failure zone propagates with the spreading superposed tensile stress waves. Moreover, the position of tensile stress waves superposed move near the free face by shortening the length of the burden and then the failure zone around the free face becomes to be remarkable. The superposed stress waves can also be controlled by changing the hole spacing, leading to the change of failure zone. Besides, the delay time also effects the failure generation inside the rock mass because the superposition of tensile stress waves is changed. Hence the position and size of the failure zone can be controlled by changing the delay time. This result shows that the flight direction of the fragmented rock may be controlled by setting an appropriate delay time. Besides, the delay time has an obvious impact on the size of failure zone and the sizes of fragmented rocks are changed due to the different delay time. Once the size of fragmented rocks can be controlled by the appropriate delay time without changing any other blasting design such as the amount of explosives, the burden, the hole spacing, it can create additional cost savings.

Chapter 4 describes the flight characteristic of fragmented rocks induced by bench blasting and proposes guidelines for preventing and controlling flyrock accidents based on the results of field tests. In the field tests, flight characteristics of fragmented rocks were captured by high-speed camera and then the maximum initial velocity of the rocks was calculated by the image analysis. From the results of a series of field tests, it can be found that both blasting designs and rock mass conditions have obvious impacts on the maximum initial velocity of fragmented rocks. In this research, the rock mass condition is evaluated by using the Rock Mass Rating (RMR) System which is widely used as the rock mass classification system in mining and civil engineering fields. Based on the results of quantitative assessments of the flight characteristic of fragmented rocks, the powder factor, the burden, the delay time and the value of RMR of the rock mass were chosen as major parameters. By using these four parameters, the prediction equation for the maximum initial velocity of fragmented rocks is developed by a multiple regression analysis. By using this equation, the maximum flight distance of fragmented rocks can be estimated. Moreover, the flight directions of fragmented rocks are strongly affected by the direction of the dominant joint system of the rock mass. In case that the strike of joint system is from 0° to 30° or from 60° to 90° against the direction of the bench face, the fragmented rocks tend to fly perpendicular to the bench face. On the other hand, in the case that the strike of joint system is from 30° to 60° against the direction of the bench face, the fragmented rocks are likely to fly not perpendicular to the bench face but to the strike of the joint system and the flight directions of fragmented rocks vary. From these results, it can be concluded that the rock mass conditions have to be investigated first and then the appropriate blasting standard should be determined based on the maximum flight distance of fragmented rocks predicted by using the proposed prediction equation of the maximum initial velocity and their estimated flight direction in order to prevent the occurrence of flyrock.

Chapter 5 discusses the size control method of fragmented rocks induced by bench blasting in open pit mine. Based on the results of a series of field tests, it can be found that both blasting designs and rock mass conditions strongly affect the size distribution of fragmented rocks. The smaller the strength of the rock is and the larger the number of crack density of rock mass is, the smaller the average particle size of fragmented rocks is. Especially, as the crack density of rock mass has an obvious impact on it, the crack density of rock mass should be assessed first when a blasting design is decided. Under similar rock mass conditions, the average size of fragmented rocks can be changed effectively by changing the amount of charge explosive and the burden. On the other hand, the hole spacing has no obvious impact on the average size of fragmented rocks. Hence, the average size of fragmented rocks can be controlled efficiently and safely by altering the burden and/or the amount of charge explosive in accordance with the guideline for prevention of flyrock proposed in Chapter 4. Additionally, the delay time and the firing pattern also have an impact on the size distribution of fragmented rocks. The delay time affects the average size of fragmented rocks and the firing pattern affects the standard deviation of fragmented rocks. By applying two-directional firing pattern that the order of ignition of blast holes is from the center to both ends of the row, the standard deviation of fragmented rocks become to be small compared with that by applying one-directional firing pattern which is the order of ignition of blast holes from one side to the other. Depending on the rock mass conditions and products specification, the size distribution of fragmented rocks can be controlled by applying the appropriate delay time and/or firing pattern.

Chapter 6 concludes the results of this research.