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Study on Prediction of Ground Vibration in Consideration of Damping Effect by Fragment in the Rock Mass

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Abstract

In modern mining industry, rock blasting is one of the essential working for rock breakage in terms of economic and efficient aspects. Blast-induced ground vibration may give serious impacts on wide range of surrounding environment, so it has to be paid much attention in the blasting process. Peak Particle Velocity (PPV) is one of the most important parameters related with blast-induced ground vibration. The prediction of PPV is very important in order to design an appropriate blasting standard and minimize its environmental impacts. However, general prediction equations and/or methods have not been developed yet because they do not consider the impact of rock mass and geological conditions. Therefore, in this paper, indoor tests, field tests and numerical simulation were conducted for assessing the effect of fragment in the rock mass on propagation behavior of ground vibration. In order to enable versatile vibration prediction at different sites with different blasting and geological condition, we investigated the differences in vibration behaviors due to blasting design, and the difference in geological condition. The result of a series of tests suggested that fragments in the rock mass related with the damping behavior of the blast-induced ground vibrations and more accurate prediction of the ground vibration (PPV) could be performed by considering fragment condition in the rock mass.

Keywords

Blasting, PPV, Numerical Simulation, LS-DYNA, Fragment

1. Introduction

The blasting technique is widely adopted not only in mining but also in civil engineering works such as tunnels, subways, highways, or dams, from efficient aspects [1]. However, the blasting technique is strictly limited by law as it may have serious effects on the surrounding environment such as ground vibration, noise, or dust. In particular, blast-induced ground vibration due to explosion can serious impacts on wide range of surrounding environment; therefore, mining companies must carefully control blast-induced ground vibrations in order to minimize and eliminate damage to nearby structures [2]. A large number of researchers have already studied the blasting technique and its impacts on the surrounding environment, so the prediction equations and reduction methods of blast induced ground vibration have been proposed. Most of them adopt Peak Particle Velocity (PPV) to evaluate the degree of blast-induced seismic motion [3] [4]. However, general prediction equations and/or methods have not been developed yet because they do not fully consider the impact of rock mass and geological conditions which experimentally have a clear influence on the propagation behavior of the ground vibrations. From these points of view, laboratory tests, field tests and numerical analysis were performed in order to investigate impacts of existence of fragmentation in the rock mass on the propagation behavior of blast-induced ground vibrations and PPV in this research. In other words, we comprehended the relationship between fragment existence and Primary wave (P wave) velocity by laboratory test and examined the evaluation method of rock fragment using P wave velocity measured by a field test. As a next step, numerical simulation by the finite element method was conducted in order to establish a prediction method of blast vibrations considering fragment in the rock mass.

2. Velocity of Seismic Wave in the Rock Mass

2.1. Laboratory Experiment

According to past research, the decrease of the propagation speed of elastic waves show a proportional relationship with the existence of fragment in the rock mass [5]. Hence, the change of the elastic wave velocity under the different fragment condition was investigated with a plaster model in order to evaluate the influence of fragment in the rock mass on the P wave velocity. As shown in **Figure 1**, simulated rock with fragment was prepared by arranging a fixed number of gypsum artificial speciments in series, and P wave velocity passing through them was measured. **Table 1** shows physical properties of gypsum samples used for this tests.

Figure 2 shows the relationship between the number of fragments and P wave velocity. From this figure, a good correlation is found between the number of fragments and the P wave velocity, and the elastic wave velocity decreases as the number of fragments increases. From this result, the impact of fragment existence in the measurement section could be quantitatively evaluated by investigating the P wave velocity and its attenuation behavior.

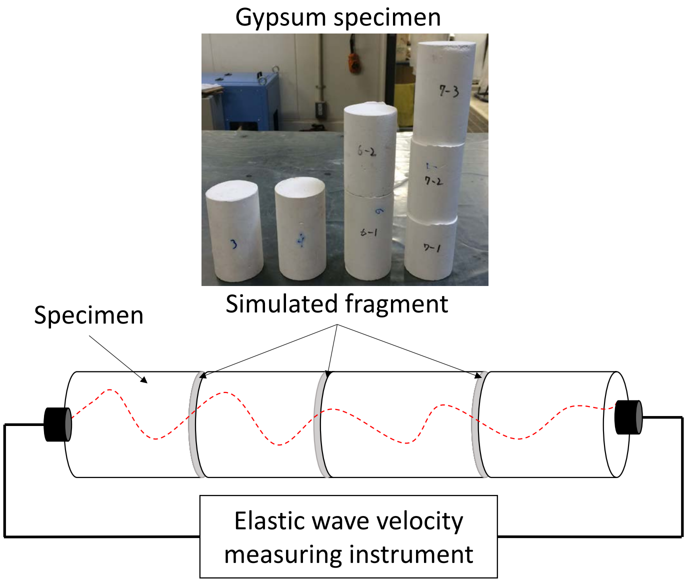


Figure 1. Outline of laboratory experiments.

Table 1. Physical properties of gypsum sample.

Number	Length (mm)	Weight (g)	Density (kg/m^3)	P wave velocity (m/s)
1	0.936×10^2	2.033×10^2	1.042×10^3	2.638×10^3
2	0.961×10^2	2.076×10^2	1.037×10^3	2.673×10^3
3	0.944×10^2	2.025×10^2	1.030×10^3	2.590×10^3
4	0.811×10^2	1.733×10^2	1.026×10^3	2.656×10^3
5	0.633×10^2	1.315×10^2	0.993×10^3	2.573×10^3
6	0.807×10^2	1.658×10^2	0.986×10^3	2.429×10^3
7	0.914×10^2	1.882×10^2	0.989×10^3	2.449×10^3

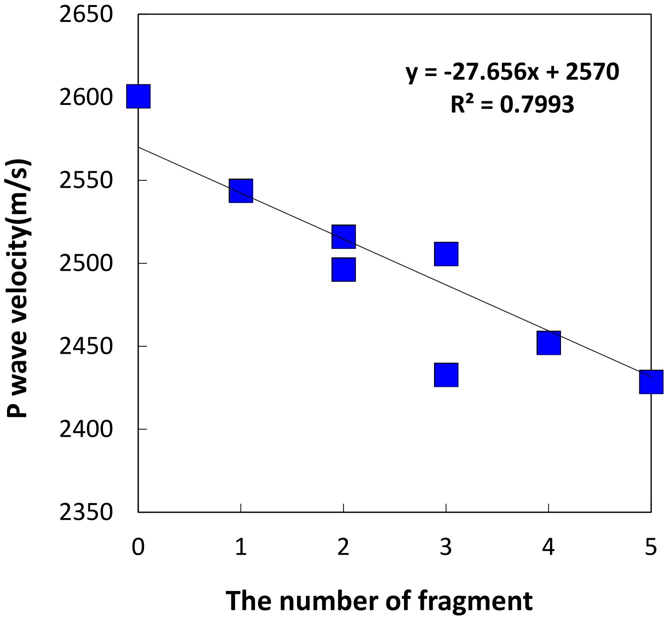


Figure 2. Relationship between the number of fragment and P wave velocity.

2.2. Field Experiment

Blast-induced ground vibration is affected by the topography and geological features of a mine site as well as charge weight and distance from the blast source [6] [7]. Hence, it is very difficult to develop a common blasting prediction equations or methods for different locations and/or geological conditions. Thus, it is necessary to comprehend the propagation behavior of blast-induced ground vibration and develop the specific prediction formula in each mine site based on the results of field measurements.

A series of field tests was conducted at I Mine in Kagoshima prefecture, Japan. In these experiments, ammonium nitrate fuel oil (ANFO) was used as an explosive. Blast-induced ground vibration was monitored with a TEAC 707z three axial piezoelectric accelerometer (max acceleration 15 g, frequency response 3 to 5000 Hz, sensitivity 100 mV/g, g = 9.8 m/s^2). In addition, a TEAC SA-611 amplifier and a LX-100 recording unit were also used. This digital recording unit can record low frequency signals and analyze waveforms with A/D converter [8]. One of the example layout of the field experiment is shown in **Figure 3**. In I Mine, hole spacing and its diameter are 2 (m) and 76 (mm), respectively. Burden is usually 2.5 (m). In addition, bench height of I Mine is 10 (m) and it angle is 80˚. Although the powder factor is depended upon operation situation, it is usually 170 (g/t). In this mine, the delay is 25 (ms).Typical blasting standard of I Mine is shown in **Table 2** [9].

The vibration sensor was installed along a traverse line set perpendicular to the row of blast holes. In these experiments, the Cartesian coordinate system is defined by the X axis parallel to the bench plane, the Y axis perpendicular to the bench plane, and the Z axis perpendicular to the ground. In addition, the piezoelectric element type pickup used in this experiment has advantages in high frequency and wide dynamic ranges measurement of vibration over the velocity type geophones or other seismometers for high sensitivity vibration since it is effective especially when examining the damping effect of vibration near the explosion source. By converting the data obtained as voltage (V) into vibration acceleration and integrating the acceleration waveform, it is possible to obtain the vibration velocity waveform and the peak particle velocity (PPV) [2]. Three to

Table 2. Typical blasting standard in I Mine.

Hole spacing	2.0 m
Hole diameter	76 mm
Burden	2.5 m
Bench angle	80˚
Bench height	10 m
Hole length	12 m
Delay time	25 ms
Powder factor	170 g/t

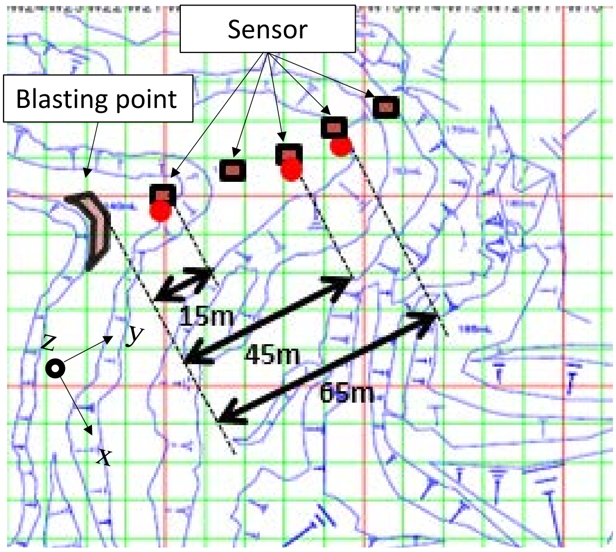


Figure 3. Example of a layout of sensor points for the ground vibration measurement.

five vibration measurement points were set from the center of the row of blast holes toward the back of the bench. **Figure 3** is one of the example of a layout of sensor points for the ground vibration measurement. In order to discuss the damping tendensy of elastic wave, each sensor was arranged as far as possible (the distance between each sensor was at least 15 m).

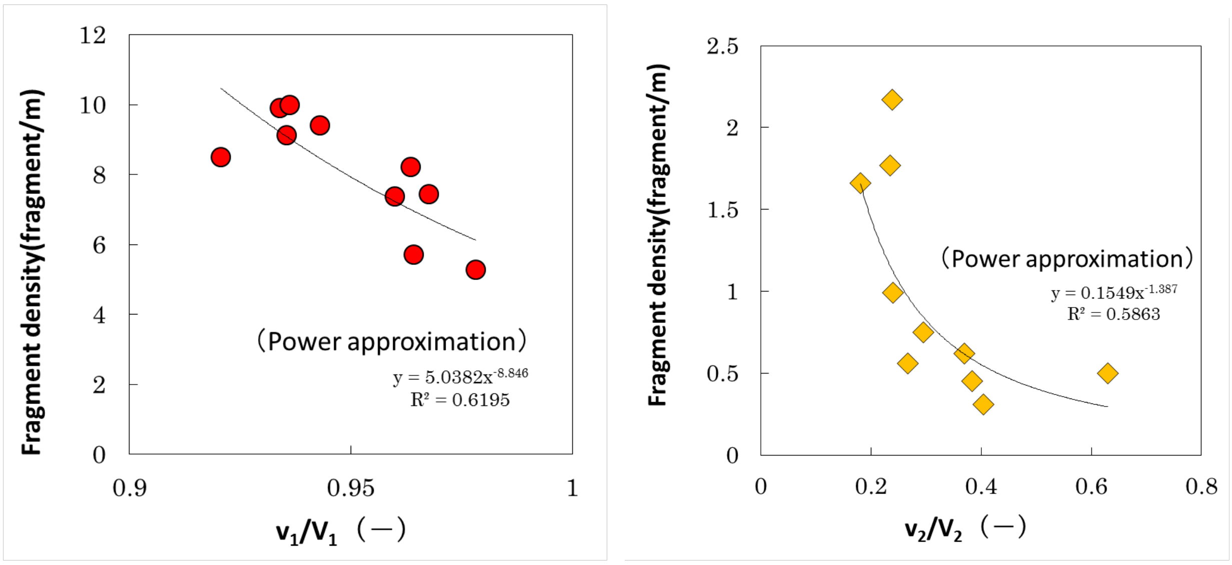
2.3. Result and Discussion

P wave velocity propagating in rock mass was calculated based on the time difference of arrival of the blast-induced ground vibration wave between vibration sensors in the field test. **Figure 4(a)** shows the relationship between the fragment density and the ratio (v_1/V_1), where v_1 is P wave velocity of the sample containing the fragments obtained in the laboratory test and V_1 is the that of the intact rock sample. Moreover, **Figure 4(b)** shows that the relationship between the fragment density, measured by the number of cracks per unit length on the blasting face in the field test [9], and the ratio (v_2/V_2), where v_2 is P wave velocity of the rock mass measured by accelerometer and V_2 is P wave velocity of the intact rock sample. Althogh the value is largely defferent due to difference of the length of measurement section and material, or effect of refelction wave in the indoor tests, these figures show similar tendency and it can be seen that fracture density increases with decreasing the value of the ratio. That is to say, fracture conditions in the rock mass can be estimated by evaluating the ratio of P wave velocity of rock mass and intact rock.

3. Study on Damping Behavior of Blast-Induced Ground Vibration Considering Fragments

3.1. Numerical Simulation Model

From the results of blast-induced ground vibration measurement at laboratory and operation site tests, it became clear that the elastic wave velocity decreases due to the existence of fragmentation intervening in the rock mass. Therefore, for more detailed discussion, we simulated the propagation behavior of the blast-induced ground vibration by means of two-dimensional finite element analysis code LS-DYNA [10] in order to investigate the influence of the fragment in the rock mass. Figure 5 shows the analysis model, and Table 3 shows the input physical property values for elastic material models.



(a) (b)

Figure 4. Relationship between fragment density and (a) v_1/V_1 (laboratory test) and (b) v_2/V_2 (field test).

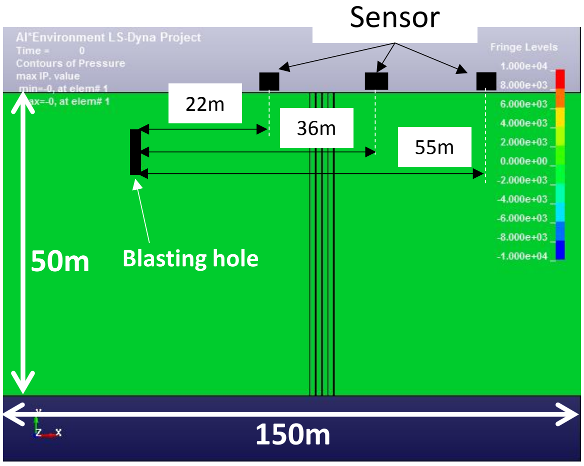


Figure 5. Numerical simulation model.

Table 3. Input parameters for numerical simulation.

	Density (kg/m^3)	Poisson's ratio (−)	Young's modulus (GPa)
Rock mass	2.37×10^3	0.27	1.91
Intact rock	2.37×10^3	0.22	58.43

Generally, the stress wave around the explosion source is expressed by the pressure function of the Equation (1) [11].

$$P(t) = P_0\,\xi\left\{(At) - \exp(-Bt)\right\} \tag{1}$$

Here, $P(t)$ is the pressure (MPa), P_0 is the maximum pressure (MPa), and ξ, A, B are constants. At that time, assuming that 10% of the detonating pressure contributed to the vibration, and the velocity of detonation of the ANFO explosive was estimated as 3000 (m/s) in consideration of the energy consumed by such a rock breaking. Based on the detonation velocity of ANFO and length of explosive charge, the time of reaching peak pressure is inferred 2 (ms), and $A = 375$ $B = 675$ are determined. **Figure 6** shows the pressure variation with time at blasting hole.

Moreover, the attenuation of blast-induced ground vibration is determined by its minimum frequency in this study. Therefore, Fast Fourier Transform (FFT) analysis was performed on the velocity waveform obtained from on-site test measurement, and the velocity-frequency spectra of each direction component at observation point was obtained. **Figure 7** shows one of the result of the FFT analysis. Based on the results, the minimum vibration frequency of the vibration waveform was determined as 12 Hz, and the attenuation factor corresponding to it was set.

In this study, the Young's modulus of the rock with excellent fragment was calculated using Equation (2) [5] in order to compare and comprehend the propagation behavior of stress wave under different rock mass conditions.

$$E_C = E_S\left(\frac{v_2}{V_2}\right)^2 \tag{2}$$

Here, E_c is the Young's modulus of the rock mass, v is the P wave velocity measured by accelerometers in the field test, E_s is the Young's modulus of the

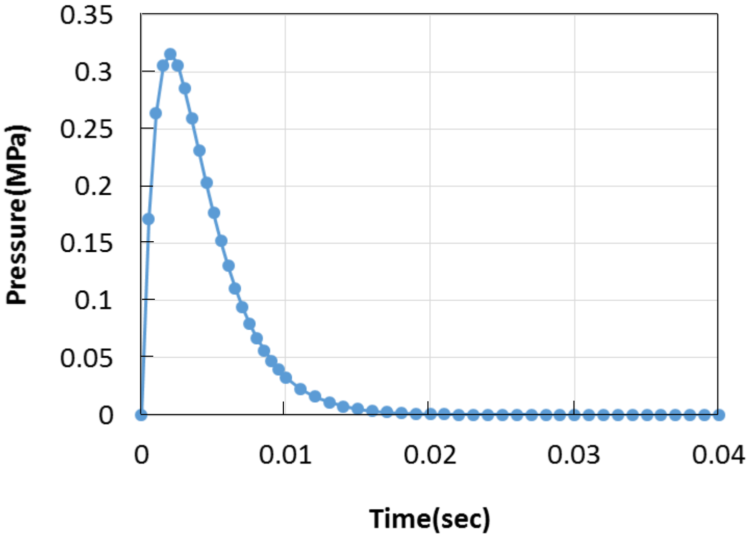


Figure 6. Relationship between pressure and the elapsed time at a blast source.

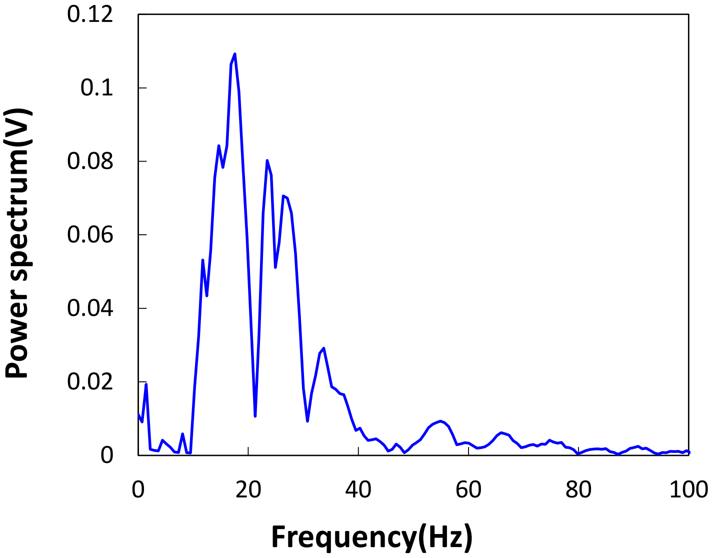
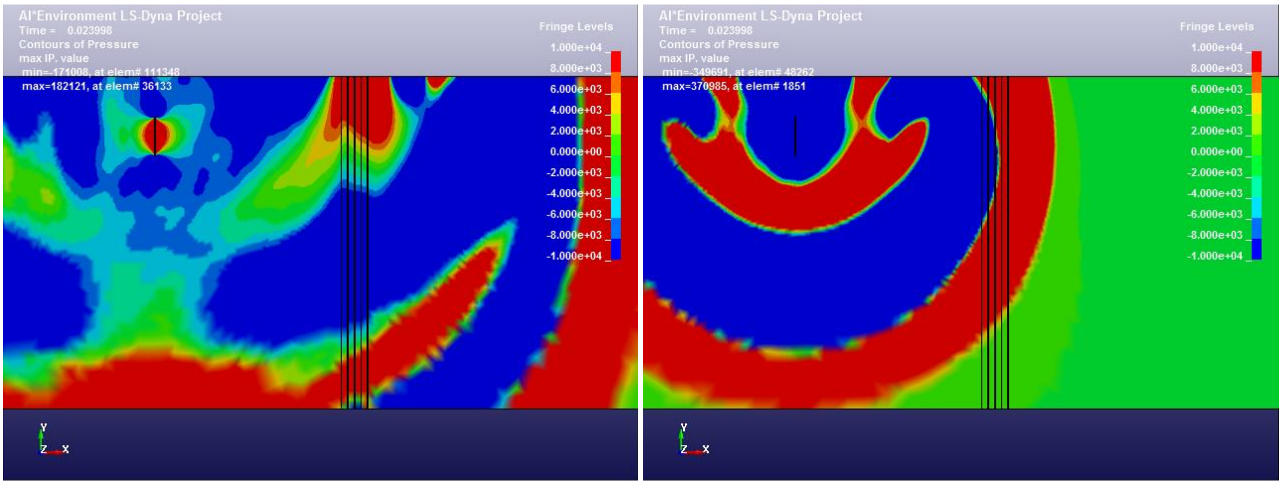


Figure 7. FFT analysis result.



(a) (b)

Figure 8. Pressure distribution of (a) intact rock and (b) rock mass at 24 ms.

intact rock sample.

3.2. Damping Effect by Fragment in the Rock Mass

Figure 8(a) and Figure 8(b) show pressure distribution diagrams of stress waves at 24 (ms) after detonation under the intact rock and rock mass condition, respectively. From both figures, it became clear that the velocity of stress wave becomes small under low Young's modulus condition. This tendency has good accordance with the result of laboratory and field tests. In other words, Young's modulus of rock mass become smaller than that of intact rock because of the existence of fragments.

As a next step, Figure 9 and Figure 10 show the relationship between scaled distance and PPV obtained from field experiment and numerical simulation,

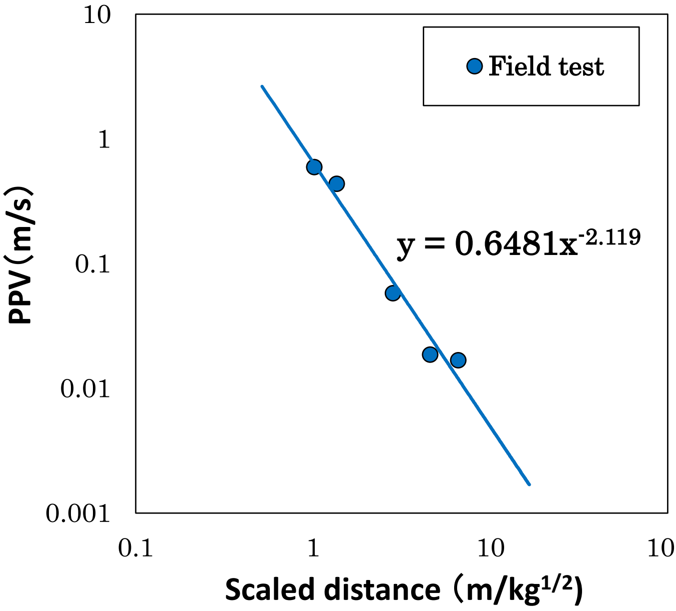


Figure 9. Damping behavior of PPV obtained from the field experiment.

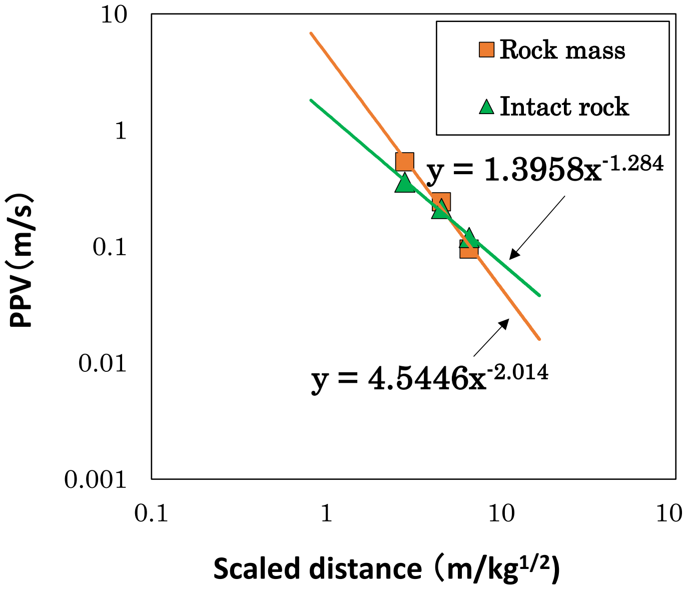


Figure 10. Damping behavior of PPV of rock mass and intact rock obtained from numerical simulation.

respectively. Comparing the slope of the approximate linear, which means the damping coefficient of the blast-induced ground vibration, the damping coefficient obtained from numerical simulation considering the existence of fragments, −2.01, has good accordance with that obtained from field experiment measurement, −2.12. Based on this result, it can be concluded that the propagation behavior and PPV can be more accurately simulated and predicted by considering fragment condition in the rock mass. In other words, the PPV might be efficiently predicted by conducting test blasting, leading to economical mining operation. Although further test blasting in other mines or quarries, this prediction method is P wave based prediction method and this technique might be applied every mine or quarry.

4. Conclusion

As a result of various investigations of influence of fragments in the rock mass on blast-induced ground vibrations, it is possible to evaluate the existence state of the fragments in the target section by measuring the P wave velocity. Moreover, it was possible to confirm the declining trend of the P wave velocity due to the fragment. Furthermore, the attenuation behavior at the site could be successfully simulated by numerical analysis by considering the existence of the fragment. This result shows that we can more accurately predict the ground vibration by using numerical model considering fragment condition in the rock mass.

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