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Research Article

Full-Scale Tests for Assessing Blasting-Induced Vibration and Noise

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Vibration and noise problems caused by a number of construction processes, specifically blasting for infrastructure development, are becoming important because of their civil appeal. In this study, a square root equation (SRE) with a 95% confidence level was proposed for predicting blasting-induced vibration through full-scale test blasting, and the vibration value predicted from this equation was located between the values predicted from the USBM (US Department of Interior, Bureau of Mines), NOF (Nippon Oil & Fats Co., Ltd.), and MCT (Ministry of Construction and Transportation) equations. Additionally, by comparing the measured noise level at full-scale test blasting with the calculated noise levels from several noise prediction equations, it was determined that the noise level predicted by the ONECRC equation had the best agreement with the measured results. However, in cases where blasting includes tunnel excavation, simultaneous measurement of vibration and noise is required to prevent damage to the surrounding facilities.

1. Introduction

Generally, in developing and developed countries, the expansion of national infrastructure and the number of highways, railways, subways, ports, and residential land development and redevelopment are increasing. Such construction requires underground excavation through rock cutting and breakage, underground drilling and piling, and ground compaction, and thus environmental damage caused by the inevitable vibration, noise, and dust also increases continuously. Recently, it has become one of the main causes of environmentally related social conflicts [1]. Along with noise, vibrations due to blasting are considered to be a major environmental damage factor, and they have significant meaning in terms of construction's disaster prevention.

The magnitude of the vibration varies depending on the type and characteristics of the explosive, the amount of charges, the method of explosion, the state of tamping or density of loading, the size of the free surface, the distance between the explosives and the measuring point, the geological condition, and other factors. The maximum charge per delay ignition over regularly spaced intervals due to the usage of a delay detonator and the distance from the explosives are the factors affecting the propagation characteristics of the vibration. When the relationship between the true maximum vector sum and the scaled distance from the detection data of vibration is represented on the full logarithmic scale, and the linear regression is based on the method of least squares, it is possible to derive a linear correlation that reflects the propagation characteristics of the vibration. This is the common practice for presenting blast-induced vibration.

Many researchers have made great efforts to theoretically understand the propagation characteristics of such vibrations [2–16]. Based on the dimensional analysis of variables related to the blasting phenomenon, they presented that the vibration velocity of the ground, which is a measure of the damage of the surface structure, can be represented in an empirical relationship by using the maximum charge per delay and the distance from the explosives as parameters. By including their studies and the empirical research result, the relationship can be expressed as (1) with the maximum charge per delay and the distance from the explosives as the main variables. On the other hand, in Japan, it is expressed in the form of (2), called the location characteristic conversion formula.

$$V = \mathrm{K}\left(\frac{D}{W^b}\right)^n \quad (1)$$

$$V = \mathrm{K}W^m D^n \quad (2)$$

Here, V is the vibration velocity of the ground (particle velocity, cm/sec), D is the distance from the blasting source to the point of measurement (m), and W is the amount of charge per delay (kg/delay). Additionally, K, n, and m are constants that depend on the rock condition of geological features and the blasting condition, and 1/2 or 1/3 is used for b. In (1), D/W^b is Scaled Distance (SD), and if b is 1/2 then it is called Square Root Scaled Distance (SRSD) [17]; if b is 1/3, it is called Cube Root Scaled Distance (CRSD) [8, 18]. It is known that the equations using these scaled distances are linear on the log-log paper, and it is appropriate to use the cubic root equation for short distances and the square root equation for long distances [19]. This study analyzes the size of cataclasite rock according to the type of Stage Advance V-Cut by performing the full-scale test blasting. Then, based on the result of the vibration measurement, this study compares the blasting vibration estimation with the existing blasting vibration equations in order to examine its applicability.

Blasting noise, a major construction pollution factor along with vibration, can be caused by air pressure waves generated from self-deformation accompanied by the destruction of rocks or structures and pressure waves due to ground vibrations, but it is mainly caused by air pressure waves. The methods of expressing blasting noise include sound pressure (Pa) and sound pressure level (dB). Since the sound pressure is too wide and not proportional to the human body's sensitivity, the sound pressure level, which is expressed in an index scale, is widely used. The method of obtaining the sound pressure level from the sound pressure is shown in the following [20]:

$$SPL = 20 \log \frac{P}{P_0} \quad (3)$$

Here, the SPL means the sound pressure level (dB), P is the sound pressure (wind pressure, Pa), and P_0 is the reference sound pressure (2×10^{-5} Pa), and it is the lowest sound pressure that a person can recognize. The degree of attenuation according to the distance of noise depends on the type and form of the noise source. In a typical construction machine, it can be assumed that the noise source is in the form of a point at a distance of several meters. If the noise source is assumed to be a point source of sound, the degree of attenuation according to the distance of the noise is given by the following [21]:

$$SPL = SPL_0 - 20 \log \frac{r}{r_0} \quad (4)$$

Here, the SPL is the noise prediction level (dB (A)) according to the separation distance, and SPL_0 is the synthesized noise level (dB (A)) for work classification, r is the distance (m) from the sound source to the predicted point, and r_0 is the distance (m) from the sound source to the base point, in which 15m is applied [21]. Since the human ear is insensitive to low frequencies —even if the pressure is constant regardless of frequency— the noise should be measured using a filter that is appropriately calibrated according to the human perception of the frequency. For most environmental noises, a decibel A filter is used and the measured sound pressure level using the A filter in the field is expressed in dB (A).

The blasting noise includes (as mentioned above) the distance from the blasting source, and it is influenced by the charge per delay, the tamping length, the quality of the rock, the availability of the blasting mat, and moreover the weather conditions such as the topography and temperature of the blasting site and air pressure. Wind velocity and wind direction can also be major factors. Therefore, even if the noise prediction equation is derived through test blasting, the credibility of the equation is very low, which makes it difficult to predict the noise. This study compared the noise levels obtained from the measurements with the data of the existing noise prediction equations [20, 22–25] and thus studied the applicability of the predictive equations.

Namely, in this study, despite the location restriction, full-scale test blasting in Korea was performed to analyze the particle size of crushed rocks with the type of blasting. In addition, this study proposed a blasting-induced vibration equation based on the result of vibration measurements and compared this with the existing equations to examine its applicability. Also, the applicability of the noise prediction equations is examined by comparing the noise value obtained from the blasting measurements with the noise values obtained from the existing noise prediction equations. The results of this study will contribute to the optimal blast design of Korea.

2. Full-Scale Blasting Tests

The blasting design is usually performed based on the following three methods.

(i) Methods based on empirical data such as existing design data and design factors of similar cases

(ii) Methods using a vibration formula derived from borehole test blasting using a geotechnical borehole

(iii) Methods using full-scale test blasting in the field bedrock or adjacent to the designed area to derive the vibration formula

When using existing empirical data, it is not possible to reflect the characteristics of the field bedrock, and there is no specific criterion among the data. As a result, the confidence of the design is very low. Therefore, it is desirable to determine the applicability after mutual analysis and review with the results of the test blasting performed on the field bedrock or adjacent area.

After installing the explosives at several points where the rocks appear in the borehole and installing a measuring instrument a certain distance from the borehole, the borehole test blasting is carried out. The borehole test blasting measures the elastic wave propagating the rock. This data can be used as basic data for examining the sphere of influence from blasting in actual construction and the optimal design. However, since the vibration measurement results from this method are about the degree of measuring the size of the waves generated by blasting with a small amount of explosives, not about the vibration quantity generated when the force of the explosives break rock mass like actual blasting, there is a significant difference from the characteristic of vibration measured during actual blasting. Therefore, empirically, it is difficult to apply the design because the result of borehole test blasting is mostly conservative.

Finally, the full-scale test blasting is a method of testing the blasting pattern of the form to be applied in future blasting with the same pattern in the field bedrock or similar rock, which makes it the optimal pre-design test method. The full-scale test blasting has two experimental methods: large-scale blasting in a tunnel room and large-scale blasting in an open-room. The large-scale blasting in a tunnel room is a more practical method than any other test blasting since it blasts with a blasting pattern in accordance with the planned design at the tunnel site with the same rock quality as the designed area. However, this method has the following problems.

(i) It is very difficult to obtain an optimal site for test blasting. Even if it is obtained, it is practically impossible to apply a blasting pattern according to the task schedule.

(ii) Tunnel blasting differs from open blasting because it is difficult to divide the blastings. Therefore, it is necessary to perform blasting several times to obtain data for the design, which is almost impossible. Even if it is possible to perform it, it should be performed for a long time considering the time required for the work process of the site where the test blasting is performed.

(iii) When blasting, 5 to 10 measuring instruments are installed. In this case, the installation position should be a place where vibration measurement can be properly performed, and the work space to install this many instruments must be provided. However, most of the tunnels are in mountainous areas, and it is not easy to meet these conditions. If the measurement position is poor, the credibility of data for the design application also decreases.

On the other hand, for open-air blasting, the blasting pattern which will be performed in open-air can be carried out in full scale by reducing the Stage Advance V-Cut for the creation of free-side surface and tunnel blasting. It is possible to obtain all the elements necessary for the design since the location of the measuring device can be selected and preformed freely within the blasting location. However, it is impossible to analyze the excavation boundary line, the excavation field, the scattering distance of the crushing rock, and the particle size analysis of the crushing rock as in an actual tunnel. It is also impossible to analyze the overbreak of the excavation boundary line as in an actual tunnel, the advance, the scattering distance, and the particle size of the cataclastic rock. Alternately, since the vibration quantity generated during the blasting, which is the most important factor for blasting design, can be measured accurately in field bedrock or the same rock type, it can be applied in the design by deriving a highly reliable lasting vibration estimation equation for the relevant rock. Therefore, in this study, open-air blasting is performed to derive the blast vibration estimation equation.

2.1. Prediction of Blasting-Induced Vibration. As described in Section 1, the equation for estimating the blasting vibration has been proposed by a number of researchers so far. A typical example of this is the analysis of the results of blasting vibration on the quarry for around 10 years in USM by the US Department of Interior (Bureau of Mines), which is presented in the following [26]:

$$V = 160\left(\frac{D}{\sqrt{W}}\right)^{-1.6} \tag{5}$$

In addition, the Japanese gunpowder manufacturer Nippon Oil (currently NOF Corporation) proposes (6) for tunnel blasting [27].

$$\mathrm{V} = 80W^{0.75}D^{-1.5} = 80\left(\frac{D}{\sqrt{W}}\right)^{-1.5} \tag{6}$$

In Korea, also, the blast vibration estimation equation is proposed to aid in selecting the blasting method appropriate to the vibration standard and the separation distance of the security facility as well as the appropriate blasting technique. For this, (1) where $K = 160$, $n = -1.6$, which is based on the above-mentioned US Bureau of Mining with a confidence of 75% [28], is used. In December 2006, in order to improve the credibility of the reflection of the characteristics of the ground medium in Korea, the "Guidelines for the Design and Construction of Open Blast" published (7) with an 84% credibility using $K = 200$, $n = -1.6$ [29].

$$\mathrm{V} = 200\left(\frac{D}{\sqrt{W}}\right)^{-1.6} \tag{7}$$

2.2. Prediction of Blasting-Induced Noise. Noises refer to an undesirable sound in terms of the human senses with the frequency of the audible range (20 to 20,000 Hz) among the sound waves due to the vibration of the air. In general, the undesired sound is defined as noise. Whether or not the sound is desired is often based on subjective human judgment, and it is impossible to accurately define it as a physical quantitative objective. However, in general, noise is considered to be a particularly loud sound, an unpleasant sound or an impact sound, a sound that interferes with listening to music or other voices, a sound that interferes with one's concentration or work, and thus a sound caused by blasting can be classified as noise. The unit is dB (A), and when the frequency magnitude changes, the sensory size of the sound pressure level varies with the human body, so the value is corrected based on the sensory sensitivity curve which is based on the center frequency of 1,000Hz

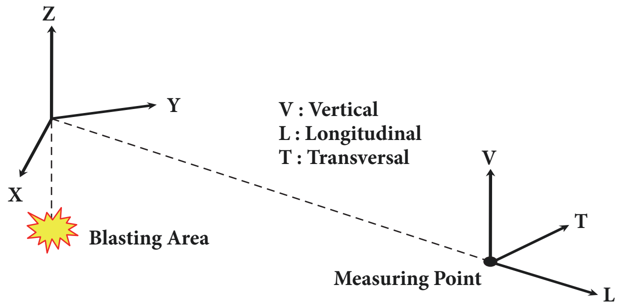


Figure 1: Schematic diagram on directions of blasting-induced vibration.

[30]. Siskind et al. [20] is shown in (8) as a noise prediction equation.

$$dB(A) = 20\log\left(\frac{P}{P_0}\right), \quad \mathrm{P} = 82\left(\frac{\mathrm{D}}{W^{1/3}}\right)^{-1.2} \tag{8}$$

Here, P_0 is the reference sound pressure (2×10^{-5} Pa), W is the maximum charge per kg (kg/delay), and D is the distance from the source (m). ONECRC [23] proposed (9) as a noise prediction equation.

$$dB(A) = -16.02\log\left(\frac{\mathrm{D}}{W^{1/3}}\right) + 97.46 \tag{9}$$

Here, W is the maximum charge per delay (kg/delay), and D is the distance from the source (m). IOERSNU [24] presented the following equation as a noise prediction equation:

$$dB(A) = -14.05\log\left(\frac{\mathrm{D}}{W^{1/3}}\right) + 97.46 \tag{10}$$

where W is the maximum charge per delay (kg/delay) and D is the distance from the source (m). Yang and Kim [22] proposed a noise prediction equation shown in the following:

$$dB(A) = -14.0\log\left(\frac{\mathrm{D}}{W^{1/3}}\right) + 88.1 \tag{11}$$

Crocker [25] presented (12) as a predictive equation for the reduction of blasting noise caused by semispherical wave attenuation.

$$dB(A) = 120 - SPL \tag{12}$$

Here, $SPL = 20\log r - 8$ and r is the distance (m) from the source to the predicted point.

2.3. Specifications to Measure Blasting Vibrations and Noise. The instrument used for measuring vibrations and noise during test blasting is one BlastMate II, one BlastMate III, and three Minate 077 from the company Instantel in Canada and one SSU2000DK and one NOMIS NS 5400 from the company Geosonics in the US. These devices can measure ground vibrations as a dedicated device for blasting vibration and noise generated by blasting. The basic equipment configuration is shown in Figure 1 and is composed of a three-axis transducer to detect ground vibrations in three directions: the vertical direction, longitudinal direction, and transversal direction of the vibration source proceeding from the width source, a sound level meter for sensing the blasting wind pressure transmitted to the air A, and a monitor for controlling and recording the measurement. For each vibration occurrence, the maximum particle velocity, the maximum particle displacement, the maximum particle acceleration, the frequency at the maximum velocity, the maximum vector sum rate, and the noise information for three directional components are produced and shown. Figures 2 and 3 represent Geosonics SSU2000DK and Blastmate Series, respectively.

(a) Portable seismic

(b) Microseismographs

Figure 2: Shape of Geosonics SSU2000DK.

2.4. Performing Full-Scale Blasting Test. The key problem with using equations for estimating the blasting-induced vibration and noise proposed in Sections 2.1 and 2.2 is that they are not site-specific. Hence, in this study, the full-scale test blasting was conducted. For this test, the rocks were composed of dacite, and an electric detonator (MS detonator) and a New Emulite 150 (160 g/ea × 32 mm diameter × width 200 mm) for explosives were used. The test blasting was carried out five times: V-cut full-scale blasting, cylinder-cut full-scale blasting, cylinder Stage Advance V-Cut blasting, cylinder Stage Advance V-Cut blasting, and Stage Advance V-Cut. Herein, the diameter of the empty hole at the time of the cylinder blasting was 102 mm. The conditions and patterns of

(a) Blastmate II (b) Blastmate III (c) Minate 077

Figure 3: Shape of Blastmate series.

Table 1: Conditions of each test blasting.

Test Number	#1	#2	#3	#4	#5
Blasting method	V-cut (Real scale)	Cylinder-cut (Real scale)	Cylinder-cut	Cylinder-cut	V-cut
Blasthole					
Diameter	45 mm	45 mm	45 mm	45 mm	45 mm
Length	2200 mm	2200 mm	2200 mm	2200 mm	2200 mm
Explosive	Emulsion	Emulsion	Emulsion	Emulsion	Emulsion
Number of blasthole	32	36	14	14	16
Total charge	30.76 kg	34.56 kg	11.52 kg	15.36 kg	15.36 kg

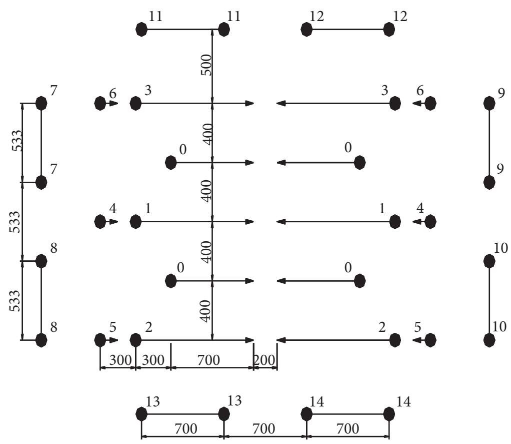
the test blasting for each test are shown in Table 1 and Figures 4–7. The drilling operation condition and blasting operation preparation conditions are shown in Figures 8 and 9.

3. Results of Test Blasting

3.1. Particle Size Analysis of Blasted Rocks by Type of Cylinder-Cut Blasting. Cylinder-cut (Test # 4) and V-cut (Test # 5) blastings were performed to confirm the blasting rock condition. As a result, the particle diameter of the crushed rocks was 40~50cm in the case of the cylinder blasting and 30~60cm in the case of the V-cut blasting (Figure 10). WipFrag, a digital particle size analysis program, was used to analyze the particle size of the crushed rocks. WipFrag analyzes the particle size of blasted or crushed rocks by inputting images or photographs. The results of the image processing by this program, the resulting crushed particle size distribution curve, and the crushed particle size cumulative curve obtained by cylinder blast blasting (average particle diameter 8.8 cm) and V-cut blasting (average particle diameter 10.5cm) did not show any significant differences. The digging lengths of Test #4 and Test #5 are 2.2m. Generally, the cut blast design is determined with the digging length. If the digging lengths match, the size of the crushed rocks seems to be similar as well. The image processing results of the crushed rocks for Test #4 and Test #5 and the crushing particle size distribution curve and the crushing particle size accumulation curve are shown in Figures 11 and 12, respectively.

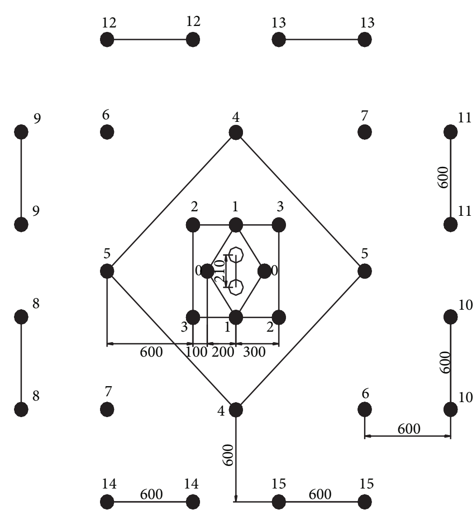
3.2. Results of Vibration Measurements. Table 2 shows the results of the vibration measurements at the actual scale test blasting. It is typical to select the most adequate equation after calculating each constant through regression analysis from the measurement data which shows the propagation characteristics of blasting vibration. Therefore, for the vector sum of the three components of the blasting vibration, which are the vertical direction (V, Vertical), direction of progress (L, Longitudinal), and direction of tangent (T, Transversal), this study deduced an equation which shows a level of vibration of 50% (Confidence level 50%) and an equation which includes 95% of the data (Confidence level 95%) by using the square root scale distance and cube root scale distance methods. Thus, from this, the blast vibration estimation equation was determined to be the most suitable equation. The linear regression results and the derived coefficients for the SRSD and CRSD are shown in Figure 13 and Table 3.

3.3. Determination of Vibration Estimation Equation for the Blasting Design. The charge per delay based on the square root equation (SRE) and cube root Equation with 50% and 95% confidence levels gained from the full-scale test blasting was calculated for the following cases where the standard of vibration management was 0.2 cm/sec, 0.3 cm/sec, and 0.5 cm/sec. The results of the calculations are shown in Table 4, and the resulting graph is shown in Figure 14. The graph shows that when the confidence level is 50% and the vibration control standards are 0.2 cm/sec, 0.3 cm/sec, and 0.5 cm/sec, the SRE produces a safety level of 55 m, 45 m, and 30 m



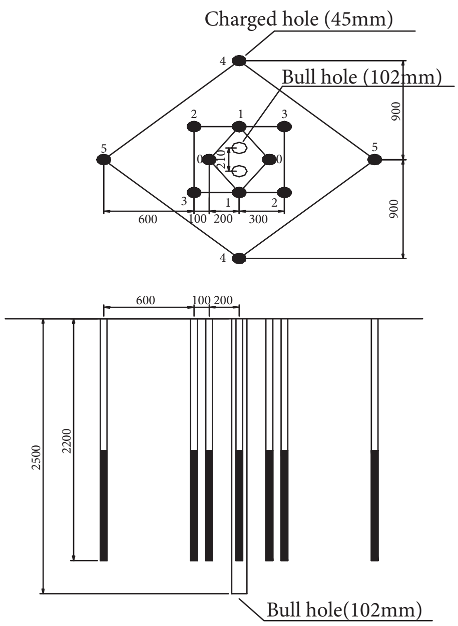
Location	Blasthole diameter (mm)	Blasthole depth (m)	Detonator No.	Number of blasthole	Charge per blasthole (kg/hole)	Charge per delay (kg/delay)
Baby-Cut	45	1.50	0	4	0.48	1.96
Center Cut (V-cut)	45	2.40	1	2	1.28	2.56
			2	2	1.28	2.56
			3	2	1.28	2.56
Supplementary center cut	45	2.30	4	2	0.96	1.92
			5	2	0.96	1.92
			6	2	0.96	1.92
Stopping	45	2.20	7	2	0.96	1.92
			8	2	0.96	1.92
			9	2	0.96	1.92
			10	2	0.96	1.92
			11	2	0.96	1.92
			12	2	0.96	1.92
			13	2	0.96	1.92
			14	2	0.96	1.92
Total				32		30.76

Figure 4: Blasting pattern (V-cut, real scale) (Test #1).



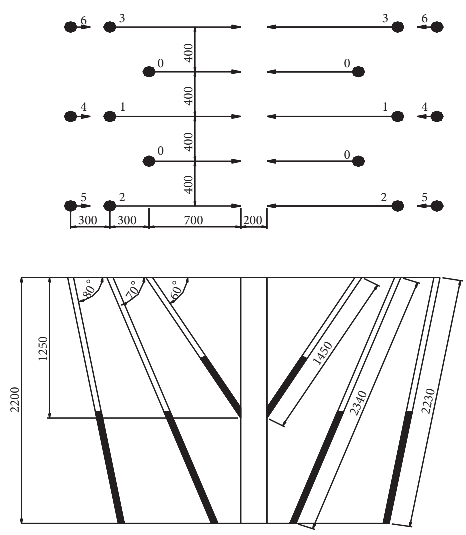
Location	Blasthole diameter (mm)	Blasthole depth (m)	Detonator No.	Number of blasthole	Charge per blasthole (kg/hole)	Charge per delay (kg/delay)
Bull hole	102	2.50	-	2	-	-
Center Cut (Cylinder-cut)	45	2.20	0	2	1.28	2.56
			1	2	1.28	2.56
			2	2	1.28	2.56
			3	2	1.28	2.56
			4	2	1.28	2.56
			5	2	1.28	2.56
Stopping	45	2.20	6	2	0.96	1.92
			7	2	0.96	1.92
			8	2	0.96	1.92
			9	2	0.96	1.92
			10	2	0.96	1.92
			11	2	0.96	1.92
			12	2	0.96	1.92
			13	2	0.96	1.92
			14	2	0.96	1.92
			15	2	0.96	1.92
Total				36		35

Figure 5: Blasting pattern (cylinder-cut, real scale) (Test #2).



Location	Blasthole diameter (mm)	Blasthole depth (m)	Detonator No.	Number of blasthole	Charge per blasthole (kg/hole)		Charge per delay (kg/delay)	
					#3	#4	#3	#4
Bull hole	105	2.50	-	2	-	-	-	-
Center Cut (Cylinder - cut)	45	2.20	0	2	0.96	1.28	1.92	2.56
			1	2	0.96	1.28	1.92	2.56
			2	2	0.96	1.28	1.92	2.56
			3	2	0.96	1.28	1.92	2.56
			4	2	0.96	1.28	1.92	2.56
			5	2	0.96	1.28	1.92	2.56
Total				14			11.52	15.36

Figure 6: Blasting pattern (cylinder-cut) (Test #3, #4).



Location	Blasthole diameter (mm)	Blasthole depth (m)	Detonator No.	Number of blasthole	Charge per blasthole (kg/hole)	Charge per delay (kg/delay)
Baby-Cut	45	1.50	0	4	0.48	1.92
Center Cut (V-cut)	45	2.40	1	2	1.28	2.56
			2	2	1.28	2.56
			3	2	1.28	2.56
Supplementary center cut	45	2.30	4	2	0.96	1.92
			5	2	0.96	1.92
			6	2	0.96	1.92
Total				16		15.36

Figure 7: Blasting pattern (V-cut) (Test #5).

compared to the CRE. When the confidence level is 95%, it produces a safety level of 105 m, 80 m, and 60 m compared to the CRE. In other words, a safety level was produced at a comparatively long distance when the SRE's confidence level was 50% and 95%. Based on the results, this paper's researchers decided to use the blasting vibration estimation with a 95% confidence level.

This study evaluates the applicability by comparing the proposed equation for estimating other blasting vibrations and the SRE with a 95% confidence level, which is determined as the blasting vibration estimation. For comparison, this study used the estimation equations from the US Department of the Interior, Bureau of Mines (USBM) [26]; the NOF Corporation [27]; and the MCT (Ministry of Construction and Transportation) of Korea [29]. These equations are used for the blast design when test blasting is not conducted. In order to compare these equations under the same conditions, this study's researchers set the maximum charge per delay at 1.0 kg to compare the vibration velocity of the ground (particle velocity, cm/sec) according to the scaled distance of the blasting vibration estimation (SD, Scaled Distance), which is shown in Figure 15. Here, the scaled distance becomes equal to the actual distance. Compared to the actual scale blasting results, the blast vibration estimation according

(a) Preparation of blasthole-drilling

(b) Drilling of blasthole

Figure 8: Performing blasthole-drilling.

(a) Blasting pattern (V-cut, real scale) (Test #1)

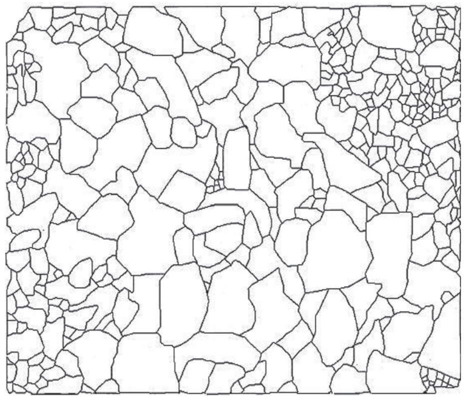
(b) Covering by blasting mat

Figure 9: Preparation of blasting.

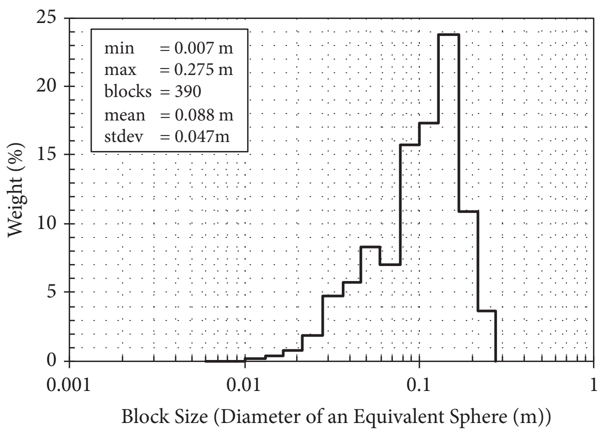
(a) Blasting pattern (V-cut) (Test #4)

(b) Blasting pattern (V-cut) (Test #5)

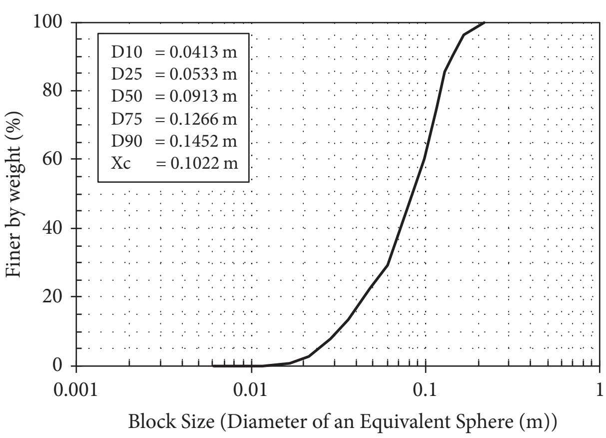
Figure 10: Shape of blasted rock with blasting method.



(a) Image-processed result

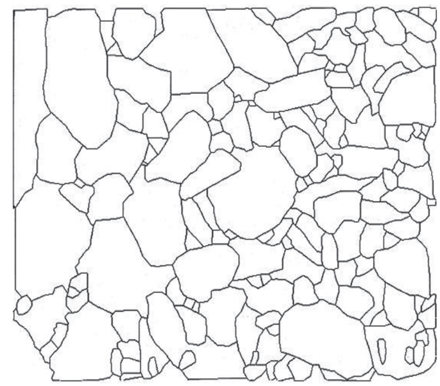


(b) Particle size histogram

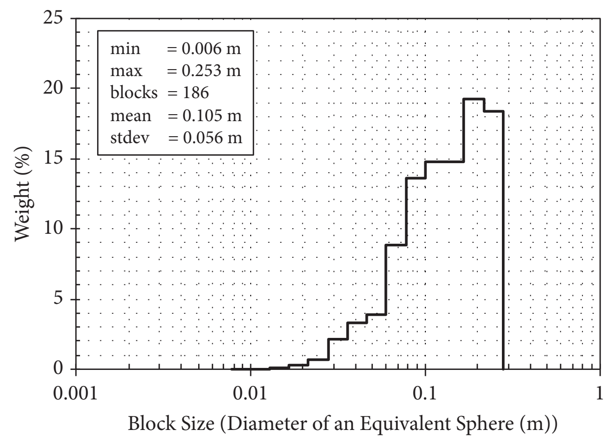


(c) Particle size distribution curve

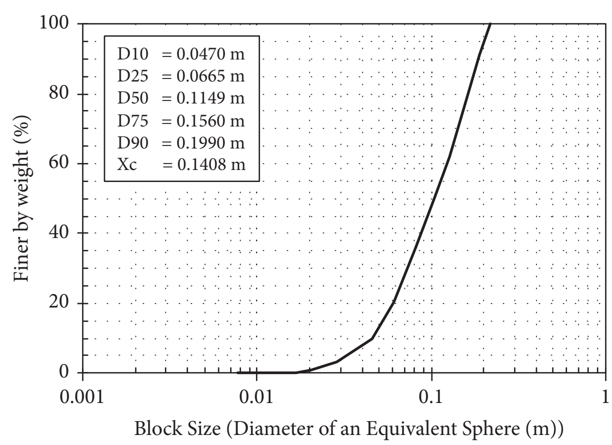
FIGURE 11: Particle size histogram and particle size distribution curve of blasted rock (WipFrag). (cylinder-cut, Test #4; Min. 0.7cm, Max. 27.5cm, Ave. 8.8cm).



(a) Image-processed result



(b) Particle size histogram



(c) Particle size distribution curve

FIGURE 12: Particle size histogram and particle size distribution curve of blasted rock (WipFrag). (V-cut, Test #5; Min. 0.6cm, Max. 25.3cm, Ave. 10.5cm).

to the distance is the most conservative in the case of the MCT of Korea, and the actual scale blasting results show a middle tendency between the Japanese full-scale blast (NOF) and the US full-scale blast (USBM). Hence, a prediction equation for blasting-induced vibration should be developed based on full-scale blasting tests in the field for the optimal blast design.

The proposed equation in this study was induced through the full-scale blasting test for field bedrock composed of dacite. Hence, this equation has the advantage and can more accurately predict blast-induced vibration than the current

Table 2: Measured results of blasting-induced vibration.

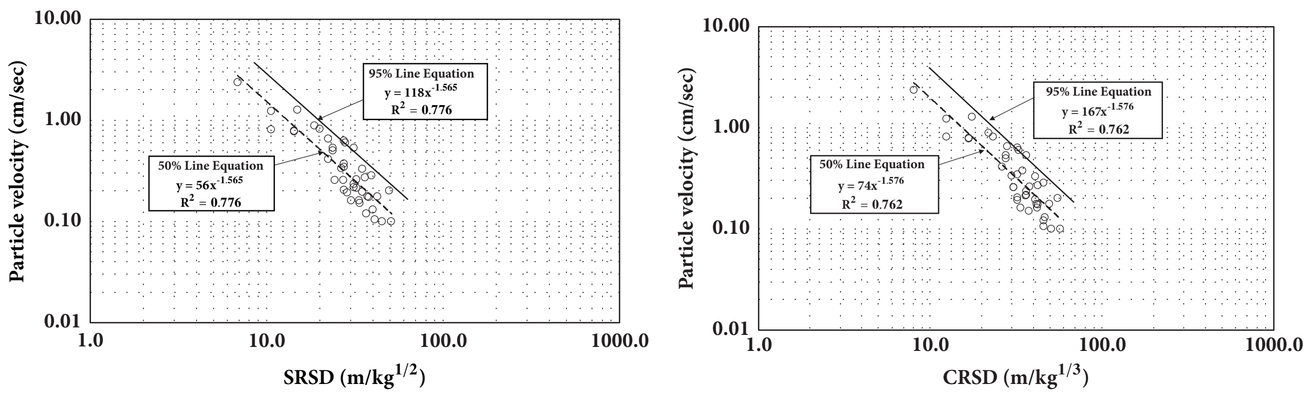
Blasting pattern	Test No.	Measuring location	Max. Charge weight (kg)	Trans. (cm/sec)	Vert. (cm/sec)	Long. (cm/sec)	PVS (cm/sec)	Distance (m)
V-cut (Real scale)	1	NO. 1	2.56	1.03	0.978	0.876	1.22	17
		NO. 2		0.762	0.356	0.381	0.787	23
		NO. 3		0.622	0.711	0.495	0.887	30
		NO. 4		0.292	0.267	0.140	0.346	44
		NO. 5		0.445	0.222	0.235	0.498	38
		NO. 6		0.45	0.20	0.40	0.53	50
		NO. 7		0.20	0.14	0.20	0.27	58
Cylinder-cut (Real scale)	2	NO. 1	2.56	0.584	0.432	0.660	0.775	23
		NO. 2		0.203	0.190	0.165	0.236	29
		NO. 3		0.324	0.254	0.330	0.410	36
		NO. 4		0.184	0.152	0.146	0.205	44
		NO. 5		0.184	0.114	0.0953	0.216	50
		NO. 6		0.25	0.05	0.30	0.33	56
		NO. 7		0.08	0.07	0.08	0.13	64
Cylinder-cut	3	NO. 1	1.92	0.127	0.762	0.241	0.257	38
		NO. 2		0.152	0.0508	0.0762	0.161	42
		NO. 3		0.146	0.0826	0.0826	0.151	47
		NO. 4		0.159	0.0572	0.0762	0.173	53
		NO. 5		-	-	-	N/A	-
		NO. 6		0.05	0.05	0.05	0.10	63
		NO. 7		0.06	0.07	0.06	0.10	71
Cylinder-cut	4	NO. 1	2.56	0.445	0.165	0.597	0.598	45
		NO. 2		0.229	0.114	0.127	0.235	50
		NO. 3		0.165	0.108	0.159	0.194	56
		NO. 4		0.222	0.127	0.184	0.284	63
		NO. 5		0.152	0.0762	0.133	0.176	68
		NO. 6		-	-	-	N/A	-
		NO. 7		0.02	0.02	0.03	0.04	81
V-cut	5	NO. 1	2.56	0.203	0.0889	0.279	0.335	37
		NO. 2		0.140	0.0762	0.140	0.193	40
		NO. 3		0.197	0.0699	0.114	0.214	45
		NO. 4		0.140	0.0635	0.114	0.176	52
		NO. 5		0.0889	0.0381	0.0635	0.105	57
		NO. 6		-	-	-	N/A	-
		NO. 7		0.14	0.08	0.13	0.20	69

Table 3: Determined parameters for square root and cube root equations with confidence levels (50%, 95%).

Parameter	Linear regression using SRSD		Linear regression using CRSD	
	50%	95%	50%	95%
K	56	118	74	167
n	-1.565	-1.565	-1.576	-1.576
R2	0.776	0.776	0.762	0.762

equations such as those proposed by USBM, NOF, and so on in dacite bedrock. However, this equation is limited because it was induced from only one study. Therefore, verification is required for this equation through continuous field tests.

3.4. Determination of Noise Estimation Equation for Blasting Design. As described in Section 1, blasting noise is greatly affected by weather conditions such as topography, temperature, air pressure, wind velocity, and wind direction of



(a) Linear regression using SRSD

(b) Linear regression using CRSD

Figure 13: Determination of equation for predicting blasting-induced vibration.

Table 4: Maximum charge per delay with vibration value and distance (unit: kg/delay).

(a) V = 0.2cm/sec

Equation	Confidence level	Distance (m)										
		10	20	30	40	50	60	70	80	90	100	110
SRE	50%	0.07	0.30	0.67	1.19	1.86	2.68	3.65	4.77	6.04	7.46	9.02
	95%	0.03	0.12	0.26	0.46	0.72	1.04	1.41	1.84	2.33	2.88	3.48
CRE	50%	0.01	0.10	0.35	0.83	1.62	2.79	4.43	6.62	9.42	12.92	17.20
	95%	0.00	0.02	0.07	0.18	0.34	0.59	0.94	1.41	2.00	2.74	3.65

(b) V = 0.3cm/sec

Equation	Confidence level	Distance (m)										
		10	20	30	40	50	60	70	80	90	100	110
SRE	50%	0.13	0.50	1.13	2.00	3.13	4.51	6.14	8.01	10.14	12.52	15.15
	95%	0.05	0.19	0.43	0.77	1.21	1.74	2.37	3.09	3.91	4.83	5.85
CRE	50%	0.03	0.22	0.75	1.79	3.49	6.04	9.59	14.31	20.38	27.96	37.21
	95%	0.01	0.05	0.16	0.38	0.74	1.28	2.04	3.04	4.33	5.94	7.90

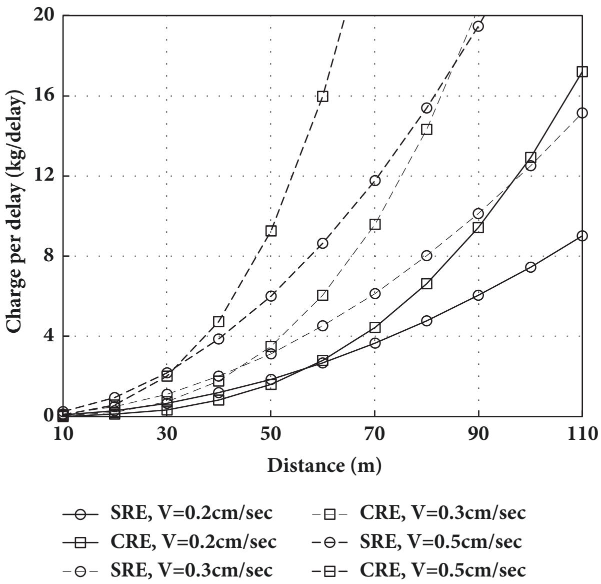
(c) V = 0.5cm/sec

Equation	Confidence level	Distance (m)										
		10	20	30	40	50	60	70	80	90	100	110
SRE	50%	0.24	0.96	2.16	3.85	6.01	8.66	11.79	15.39	19.48	24.05	29.11
	95%	0.09	0.37	0.84	1.48	2.32	3.34	4.55	5.94	7.52	9.28	11.23
CRE	50%	0.07	0.59	2.00	4.73	9.24	15.97	25.36	37.85	53.89	73.92	98.39
	95%	0.02	0.13	0.42	1.00	1.96	3.39	5.39	8.04	11.45	15.70	20.90

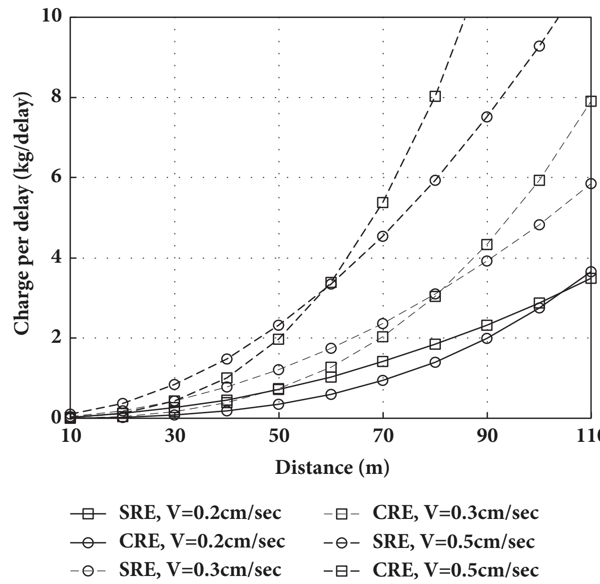
the blasting point. Therefore, even if the noise prediction formula is derived through field test blasting, the reliability of the equation is not satisfactory. Therefore, in this study, the researchers tried to compare the results of the typical noise prediction formula applied in Korea and the measured values by test blasting. A blasting point distance of 29 m was used along with the previously proposed noise prediction equations [20, 22–25], and the calculated noise level was compared as shown in Table 5 and Figure 16. As a result, the noise prediction equation of ONECRC [23] was found to be most similar to the one measured from test blasting. However, since the propagation pattern of noise varies depending on various weather conditions such as temperature and pressure, it is necessary to constantly measure and manage the noise to prevent damage to surrounding security objects when performing actual blasting operations, such as tunnel construction.

4. Conclusion

In this study, the researchers performed real scale test blasting to analyze the particle size of crushed rocks according to the type of blasting and based on the result of vibration measurement. The proposed blasting vibration equation was compared with existing equations to examine its applicability. Additionally, the applicability of the estimations was also



(a) Confidence level 50%



(b) Confidence level 95%

Figure 14: Graph of maximum charge per delay with vibration value and distance.

Table 5: Comparison among noise levels obtained from test blasting and several equations for noise prediction.

Method for obtaining noise level	Noise level (dB(A))
Test blasting	89.50
Siskind et al. [20]	80.42
Yang and Kim [22]	69.53
ONECRC [23]	96.40
IOERSNU [24]	78.82
Crocker [25]	98.75

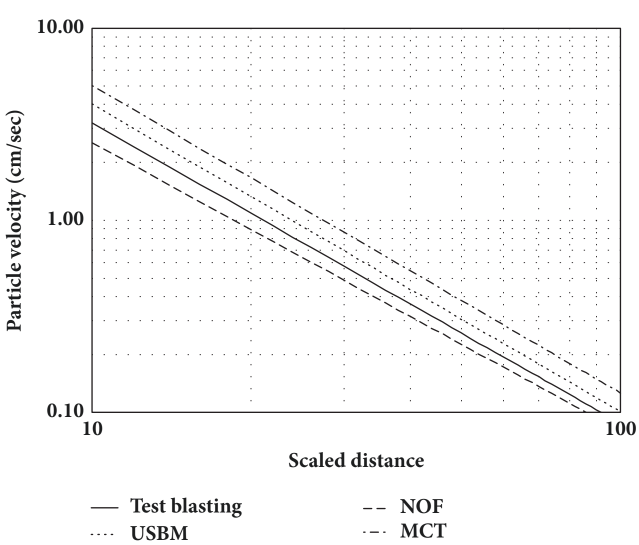


Figure 15: Comparison between tendencies of blasting-induced vibration with distance.

examined by comparing the noise values obtained from the blasting measurements with the noise values obtained from the existing noise estimations. The conclusions drawn from this are as follows.

(1) The diameters of crushed rocks in the case of cylinder and V-cut blasting were 40~50cm and 30~60cm, respectively. In addition, the fragment size distribution curve and the fragment size cumulative curve from the results of the image processing by WipFrag, a digital particle size analysis program, did not show a significant difference between the cylinder blast (average particle diameter of 8.8 cm) and the V-cut blast (average particle diameter of 10.5 cm).

(2) Based on the results of the vibration measurement from the actual scale blasting test, the square root equation and cube root equation with confidence levels of 50% and 95%, respectively, were derived. For both levels of confidence, the square root scale equation produced a better safety level at long distances than the cube root equation. Therefore, in this study, the equation at the confidence level of 95% is used for the blast vibration estimation equation.

(3) The results of the comparison between the blast vibration estimation equation obtained by actual scale blasting and the existing blast vibration estimation equations from the Japanese blast vibration (NOF), the US Bureau of Mines (USBM), and the Ministry of Construction and Transportation (MCT) of Korea showed that the MCT equation had the

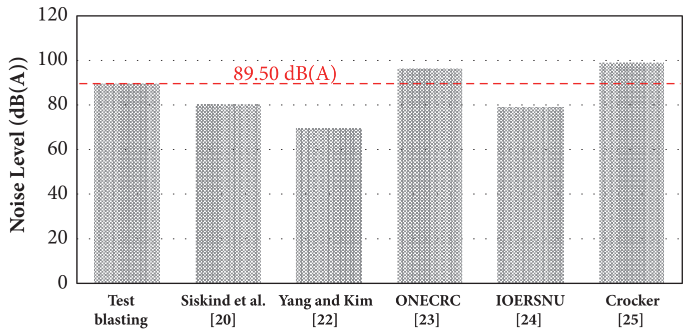


Figure 16: Graph for comparison of each noise level (based on Table 5).

most conservative result. The blasting vibration estimation equation in this study showed a middle tendency between the US and the Japanese equation.

(4) After comparing the noise levels measured by actual scale test blasting with the previously calculated noise predictions, the noise prediction equation of ONECRC [23] was found to be the most similar to the data measured from the test blasting. However, since the propagation pattern of noise varies depending on various weather conditions such as temperature and pressure, it is necessary to continuously manage the noise so as not to cause damage to surrounding security objects when performing actual blasting work, such as tunnel construction.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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