Research paper

Vibration and fragmentation by changing the blast burden at Funao limestone quarry

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Abstract

Field experiment was performed mainly to test weather or not the blast burden gives significant influence on vibration level. Parallel with the main idea, investigation was extended to measure size distribution of fragmented rocks. The relationship between peak particle velocity (PPV) and scaled distance reveal three relationships for three different scenario of burden, which indicate that the blast burden influences vibration level. Fragmentation measurements of a muckpile using digital image give plausible results. Using software known as Split Engineering, the fragmented rocks resulted from three scenario of blast burden were calculated and presented in size distribution curve.

Keywords: Vibration, Fragmentation, Blast design, Burden

1. Introduction

Rock blasting is the rock excavation technique most widely adopted in the various branches of the mining and construction industry because it is economical, reliable, and safe. The job of the explosive, which is loaded in boreholes in the rock and blasted according to a prearranged sequence, is to fracture, fragment and displace from its natural position a well-defined portion of the rock.

Among the effects of the explosion round, rock vibration at excavation contour generated by the shock wave following the explosion deserves special attention. This phenomenon is usually harmless, vibration lasts for a very short time, after which the rock reverts to its initial condition. However, the situation differs, and problems arise, in the presence of important structures likely to be particularly susceptible to dynamic stress (building, bridges, dams, etc.) because the vibration can be transmitted to them through the ground. In such cases it is necessary to check, during blast design whether the vibration-induced stress may compromise structure integrity. And where danger might be expected, it is necessary to reconsider blast design in order to reduce the vibration to acceptable levels.

In blast design, burden is believed as the most important parameter. There is general consensus amongst blasting researchers that the average fragment size decreases with decreasing burden [1)-3)]. Unfortunately less attention has been given to the effect of burden to the induced vibration. Experiments were performed in field to check whether or not burden influences the induced vibration. The works are presented with two fundamental aspects are highlighted: 1) monitoring and interpretation of blast vibration waveforms, 2) measurement of blasted rocks using image analysis.

2. Experimental works

2.1 Site description and experiment layout

Japan, a country lacking in most mineral resources, is self-sufficient in limestone. Limestone in Japan is believed to have originated billions of years ago from deposits of the shells and remains of sea creatures on the ocean

Table 1 The weight of ANFO for each blasting test.

Hole no.	B3.7m1	B3.7m2	B4.2m1	B4.2m2	B4.7m1	B4.7m2
	ANFO weight (kg)					
1	24.5	40	40	15	10	22.5
2	41	41	38	44.5	42	43.5
3	42.5	43	39	38	40	40
4	40	32	39	45	34	40
5	35	40	40	45	40	38
6	40	23.5	17	45	40	44
7	40	41	37	45	41	43
8	38	38	37	45	45	42.5
9	39	41	39	45	41	38
10	40	40	38	45	45	22.5
11	45	38	38	45	42	43
12	49	38	25		45	38
13	37	40	38		41	
14		43			42	
15					33	
16					39	
17					15	
Total	511	457.5	538.5	465	635	455

B3.7m1-2 >>Burden 3.7 m; B4.2m1-2 >>Burden 4.2 m; B4.7m1-2 >>Burden 4.7 m

floor. Over time, these remains hardened into a type of rock composed primarily of calcium carbonate ($CaCO_3$). Upheavals caused by changes in the earth's crust gradually forced this rock up from beneath the ocean.

Annual production of limestone in Japan is approximately 163 million tons [4], and the quarries naturally lie from south to north of Japan. One of the quarries is located in Fukuoka, a Funao limestone quarry. The quarry is chosen as field of investigation as it is located relatively near from the Kyushu University.

In order to minimize errors which could have been resulted by rock heterogeneity, investigations were concentrated only at one 'spot' of the quarry. The area of interest was located at the bottom of quarry. Explosive type, explosive loading density, sequence and timing detonation, spacing holes, depth of holes, and depth of inert stemming were normal for the particular quarry. Only the blast burden was determined by this study. The burdens were changed three times/three scenario (3.7 m, 4.2 m, and 4.7 m). Each scenario was repeated two times. Combination of two repetitive tests and three burdens give in total six blasting operations that had been successfully investigated in this study.

Number of holes per blasting varied from 11 to 17 holes in a row. Diameter of blasting hole is 102 mm. Ammonium Nitrate Fuel Oil (ANFO) was used as an explosive and initiated hole by hole using electric detonator delay of 500 milliseconds. The weights of ANFO inside blasting holes are given in Table 1.

Accelerometer was used as instrument to monitor ground vibration. The experiment layout, as illustrated in Fig.1, consists of four accelerometers located behind a blasting row. The monitoring points on ground surface were setup along a measuring line with various distances. Since the analysis was done hole by hole, combination of three scenario of burden with each repeated two times and four accelerometers give various distance of vibration monitoring up to 320 (Table 2).

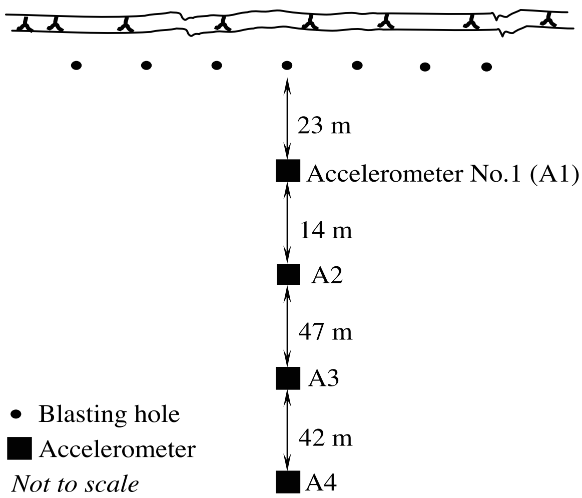

Fig. 1 Experiment layout.

Table 2 Burden scenario, monitoring distance, and number of blasting holes.

Burden scenario	Accelerometer distance measured from the center of blasting row (m)				Blasting hole (*n*)	Distance scenario (*n*)
	A1	A2	A3	A4		
3.7 m	28	42	89	131	14	56
3.7 m	19	33	80	122	13	52
4.2 m	25	51	98	140	13	52
4.2 m	21	47	94	136	17	68
4.7 m	23	37	84	126	11	44
4.7 m	15	29	70	118	12	48
		Total			80	320

2.2 Instrumentation

2.2.1 Vibration monitoring

Transducer is the front line of the vibration monitoring system, the point where some physical attribute of the blast is converted into an electrical signal. The selection of the most appropriate transducer depends on the purpose and circumstance of the measurement exercise. Geophones are fairly cheap and easy to install and used, but have limited vibration threshold. Accelerometers have no moving parts and can generally be used for low and very high frequency application. Since frequency resulted by blasting was likely expected relatively high (>100 Hz), accelerometer was then chosen as the instrument for vibration monitoring. A complication associated with the use of accelerometers is that if the cable length is changed then the associated capacitance term in the output calculation also changes, as does the sensitivity. For accelerometer used in this study, the complication was overcome using the charge amplifier at the end of the cable which converts the charge flow into voltage.

It is important to understand that the final vibration measurement will represent the reaction of both the transducer and its coupling to the imposed vibration. The coupling itself may have dynamic properties that interfere with the measurement that are being sought and great care must be taken to ensure that this effect is minimized [5]. For a reading from a transducer to be valid, the sensor must move as if it were an integral part of the rock or structures being monitored. For this study, a permanent mounting was applied. The transducer was connected to a permanent mount which were lowered into a hole to avoid spurious resonances.

The blast waveforms were stored in analog form, with tape recorder. Consequently the data must undergo a further stage of processing before it could be analyzed. This involved replaying the tape and digitizing the waveforms with a storage oscilloscope. It was taken several replay sequences before the whole event was saved to disk. Since the whole event was saved to disk in order of acceleration, another step must be done for a complete analysis was integration. This was mathematically derived to transform data to velocity.

2.2.2 Fragmentation measurement

Fragmentation assessment was achieved by the analysis of scaled photographs taken from the muckpile. Paley [6] recommended a procedure for taking muckpile photographs so as to minimize errors due to distortion. Two balls with diameter of 24 cm are used to provide scale in the photograph. The balls were placed in the same vertical line down the muckpile, preferably with one ball near the top of the muckpile and one ball near the bottom. The balls should not be placed randomly in the muckpile nor in a horizontal line across the muckpile. The camera was held such that the long axis of the photograph is vertical. The photograph was then taken with the camera as perpendicular to the muckpile surface as possible. By having two balls on the muckpile surface, allowance was made for variable scale within the photograph when the camera could not be positioned perpendicular to the muckpile surface.

The scaled fragmentation photographs were manually digitized from the original photograph on computer screen by software known as Split Engineering as illustrated in Fig. 2. The outlines of all visible rocks above a certain minimum resolution (3 mm in diameter on the photograph) were traced by mouse.

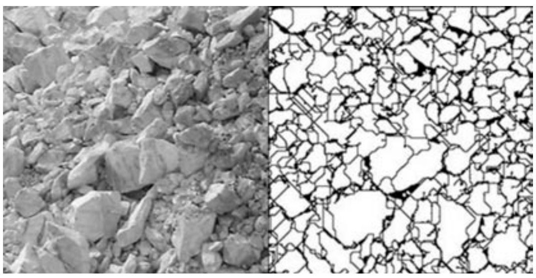

Fig. 2 Digitized fragment outlines.

3. Results and discussion

3.1 Vibration monitoring

Explosion-generated waves can be divided into three main categories: compressive, shear, and Rayleigh [7]. Compressive and shear waves are known as body waves and act within the rock mass. Rayleigh waves are generated at the ground surface in response to excitation by body waves. To describe the motions completely, three perpendicular components of motion were measured. The longitudinal component was oriented along a horizontal radius to blasting source. The other two perpendicular components were vertical and transverse to the radial direction.

A typical waveforms recorded from six blasting operations are shown in Fig. 3. The waveforms were taken from monitoring station of 23 m, 84 m and 126 m apart from blasting source with burden of 4.7 m. The waveforms clearly indicate that blasting operation was made in a series of smaller detonations which were delayed by 500 milliseconds. The most important parameters that describe the waveform are peak amplitude and frequency.

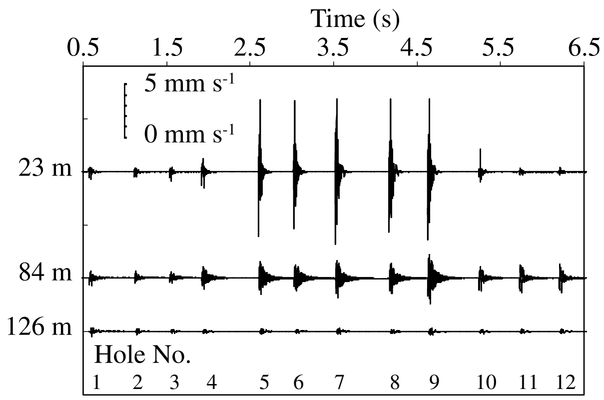

Fig. 3 A typical blast vibration waveform. (zoom out transverse motion)

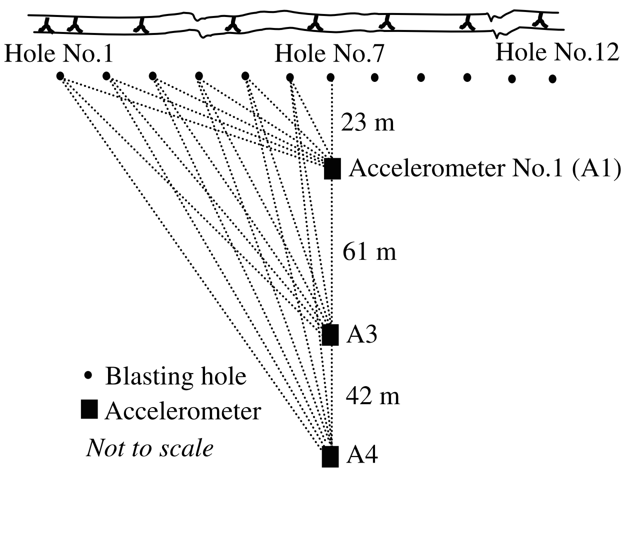

Fig. 4 The area of influence for each detonated hole.

In normal blasting operation, both parameters are dependent on explosion and transmission medium. It was found that peak amplitude ranges from 0.1 to 20 mm s^{-1}, as for frequency ranges from 65 to 200 Hz. The findings agree with investigated by Cording [8]. The ranges of typical blast parameters are 10^{-4} to 10^{3} mm s^{-1} and 0.5 to 200 Hz for particle velocity and frequency respectively.

Three groups of waveforms illustrated in Fig. 3 were taken from three monitoring points. Each waveform stands for specific monitoring distance. Within the figure, the above waveform was the closest one to the blasting source (23 m measured from the center of blasting row). The in-between waveform was the second closest to the blasting source (84 m measured from the center of blasting row). While the lowest waveform was measured 126 m from the center of blasting row. The figure generally shows that peak magnitude decrease by additional distance. This obviously indicates wave attenuate while traveling within the rock mass.

Single waveform within the overall waveforms indicates vibration produced by one detonated hole. The peak values are difference from one to the others, and this correspond to the monitoring distance and amount of detonated explosive inside the specific hole. Hole No. 7 gives the highest vibration magnitude, which is suspected occurs because of its closest monitoring distance. Otherwise, hole No. 1 gives the lowest vibration magnitude because of its farthest monitoring distance. The area of influence of each detonated hole to the vibration monitors can simply be illustrated in Fig. 4.

Figure 3 also indicates that 500 milliseconds delay has given result of no overlapping waveforms. This fact has

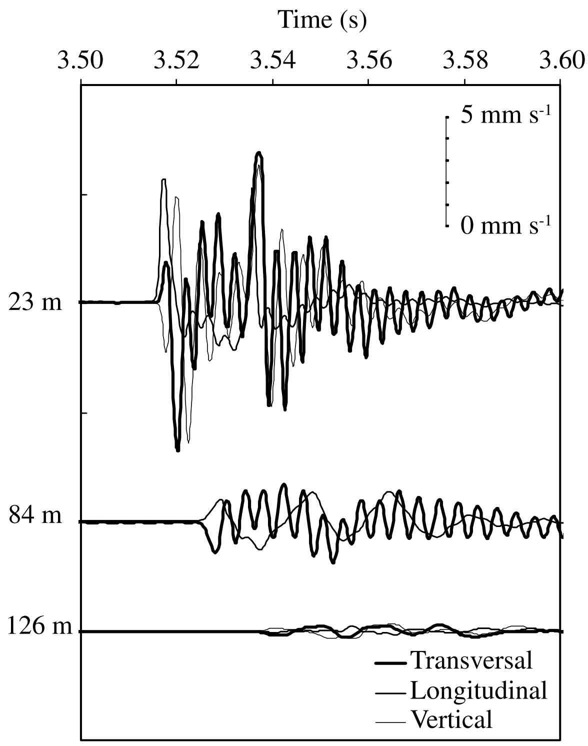

Fig. 5 A typical blast vibration waveform (zoom in).

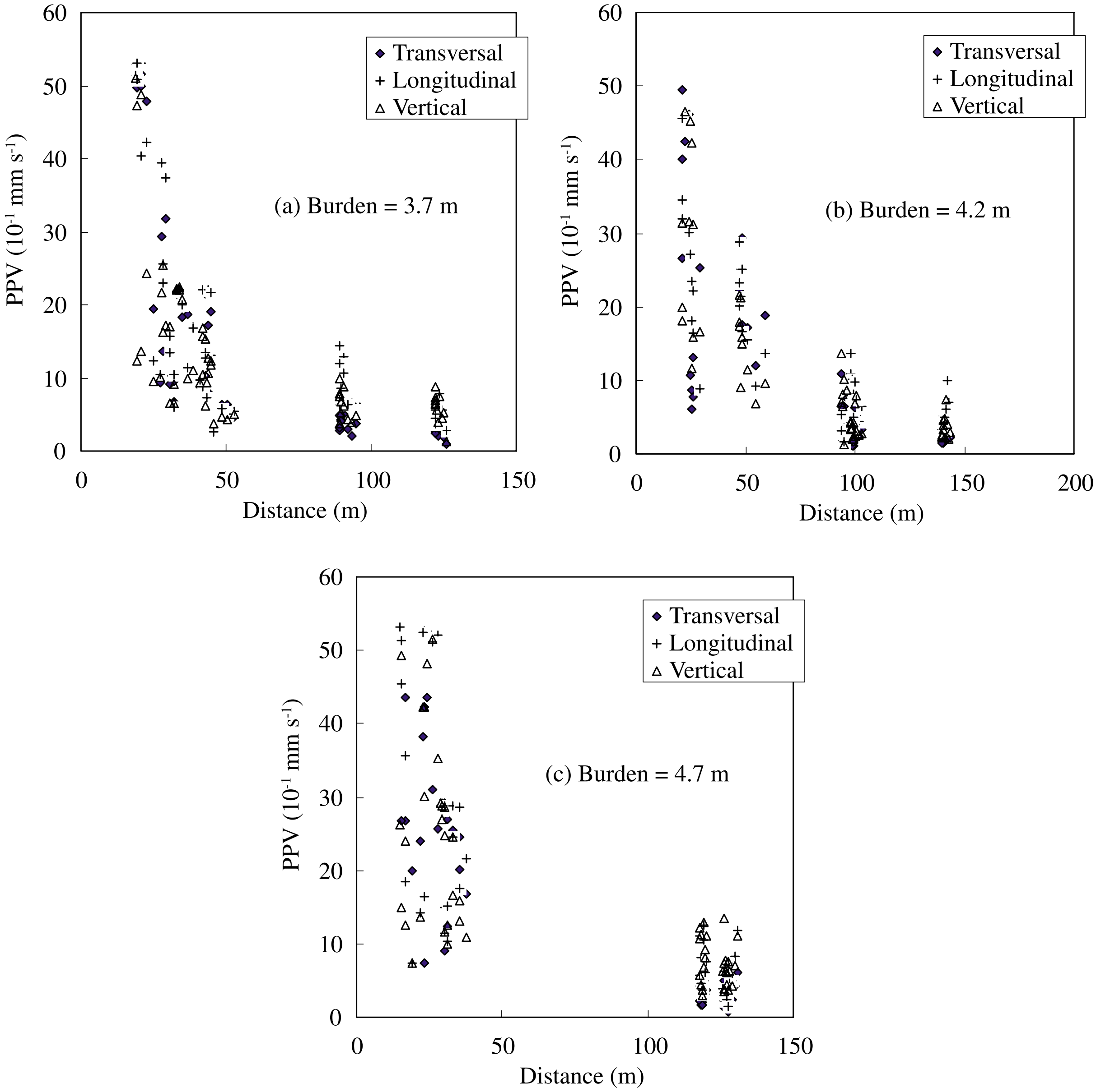

Fig. 6 PPV versus monitoring distance: (a) Burden 3.7 m; (b) Burden 4.2 m; (c) Burden 4.7 m.

simplified analysis process by enabling to consider only one single waveform for one instance detonation. This becomes important when explosive charge and distance are brought to the prediction of peak particle velocity.

Zoom in of the waveform is depicted in Fig. 5. The time scale has been managed for closer looking within the period of interest. These zooms in processes were done several times to derive the peak magnitude of all single waveforms. The peak magnitude identified vibration which is produced by one instance detonation. A typical single waveform lasts for 50 to 100 milliseconds. If the waveform was found longer than 100 milliseconds, the rest was cut and considered as noise.

Figure 5 shows there is no clearly sign of which motion comes first (whether longitudinal, transversal or vertical). The three components arrive at the same time, which theoretically should be started from the transverse motion follow by the vertical and longitudinal motions [9]. This phenomenon likely happens for body wave only. Starting movements of the motion are also found irregular. The longitudinal motions in Fig. 5 are started by positive value. Note that for other single waveforms, the longitudinal motion could be started by negative value. The irregularity also happens to the transverse and longitudinal motions.

The three groups of single waveform in Fig. 5 indicate

Table 3 Relationship between the PPV and scaled distance.

Burden	Relationship
3.7 m	$PPV = 318\ SD^{-1.046}$; k=318, a=-1.046
4.2 m	$PPV = 347\ SD^{-1.047}$; k=347, a=-1.047
4.7 m	$PPV = 405\ SD^{-1.046}$; k=405, a=-1.046

the change of frequency by distance. Waveform frequency decrease by additional monitoring distance (measured from the blasting source). For one dominant frequency of peak amplitude of longitudinal motion, it was found that frequencies at distances of 23 m, 84 m and 126 m are 109 Hz, 56 Hz and 43 Hz respectively.

Peak amplitudes of vibration velocity, later called Peak Particle Velocity (PPV), were carefully derived from each single waveform. To give general idea of how the data look like, Fig. 6 shows the PPV as a function of distance for three burden scenario. Each PPV stands for one instance detonation. The data shows scatter relationship. It is difficult to conclude from the figures whether or not burden gives influence to the peak magnitude. However, those figures indicate that explosive charge should be taking into consideration.

The classical method of predicting blast induced ground vibration is based on the establishment of an attenuation curve of vibration amplitudes [10]. The recorded PPV (true vector sum of three components of motion) are plotted as a function of scaled distance. Scaled distance is commonly used to compare vibration due to different explosives charge at varying distance from a vibration monitoring station.

Scaled distance is defined as the ratio of the distance from the blast source to monitoring point and the square root or cube root of the explosive charge initiated within a certain time interval (usually 8 milliseconds). The 8 milliseconds time interval is based on the results of investigation by Duvall [11] that show longer time intervals effectively separate the dominant part of vibration from individual holes in a single row blast. Fortunately, this has been achieved within this study by applying 500 milliseconds delay.

Since the main objective of the study is to find whether or not the blast burden influences vibration magnitude, the recorded PPV (true vector sum of three components of motion) are then plotted as a function of scaled distance ($SD=R\ W^{-1/3}$) for three burden scenario as shown in Fig. 7(a-c). Note that the PPV is specified in the order of 10^{-1}

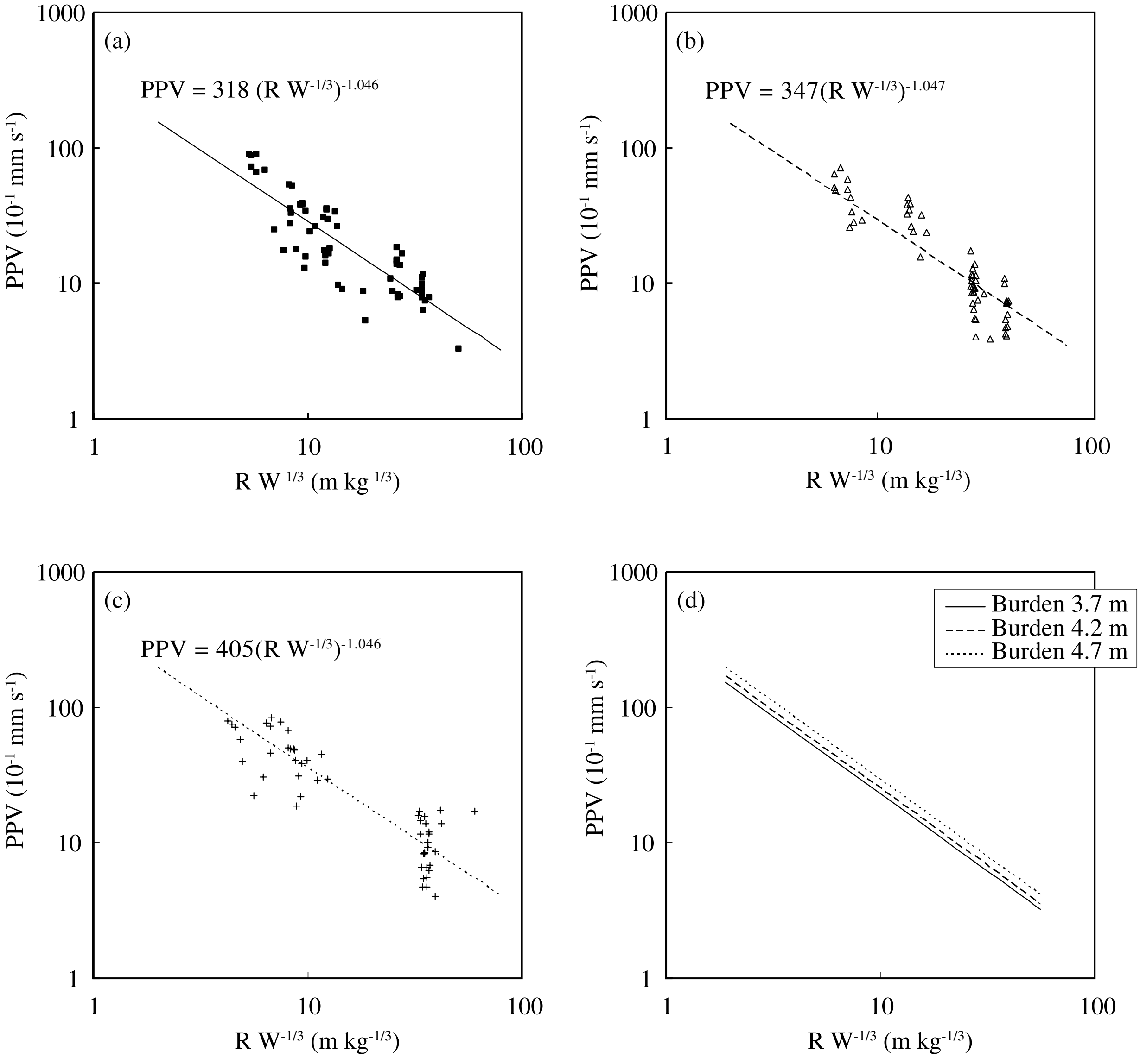

Fig. 7 PPV versus monitoring distance: (a) Burden 3.7 m; (b) Burden 4.2 m; (c) Burden 4.7 m; (d) All.

mm s-1, while the scaled distance in m kg-1/3. A slightly different relationship is obtained. Table 3 presents the fit of the relationship.

Elastic theory, through the equations of motion for spherically propagation wave from point source in an infinite body, predicts that the PPV of body waves will decay at a rate proportional to $1/R^n$ [7]. n is defined as attenuation value, a function of transmitting media. If this theory is brought to the relationship between the PPV and scaled distance, then n can be treated similarly with a, a function of transmitting media, which for rock blasting case waves travel within the rock mass. Three relationships given in Table 3 reveal almost similar value of a. This agrees with the fact since the investigations were carried within the same rock mass.

A clearly different k is found. k increases by additional burden. This indicates k is a function of burden. In graph relationship of the PPV and scaled distance, while a is kept constant, changing k will move the relationship line up or down. The line goes up if k is increased, and the line goes down if k is decreased. These phenomena can be understood when the three relationships were combined into one graph as shown in Fig. 7(d). The graph shows that the PPV increases by additional burden. To end this section, it can be concluded when burden is designed bigger than its optimum value, blasting produce higher vibration magnitude. Otherwise, when burden is designed smaller than its optimum value, blasting produces relatively low vibration magnitude.

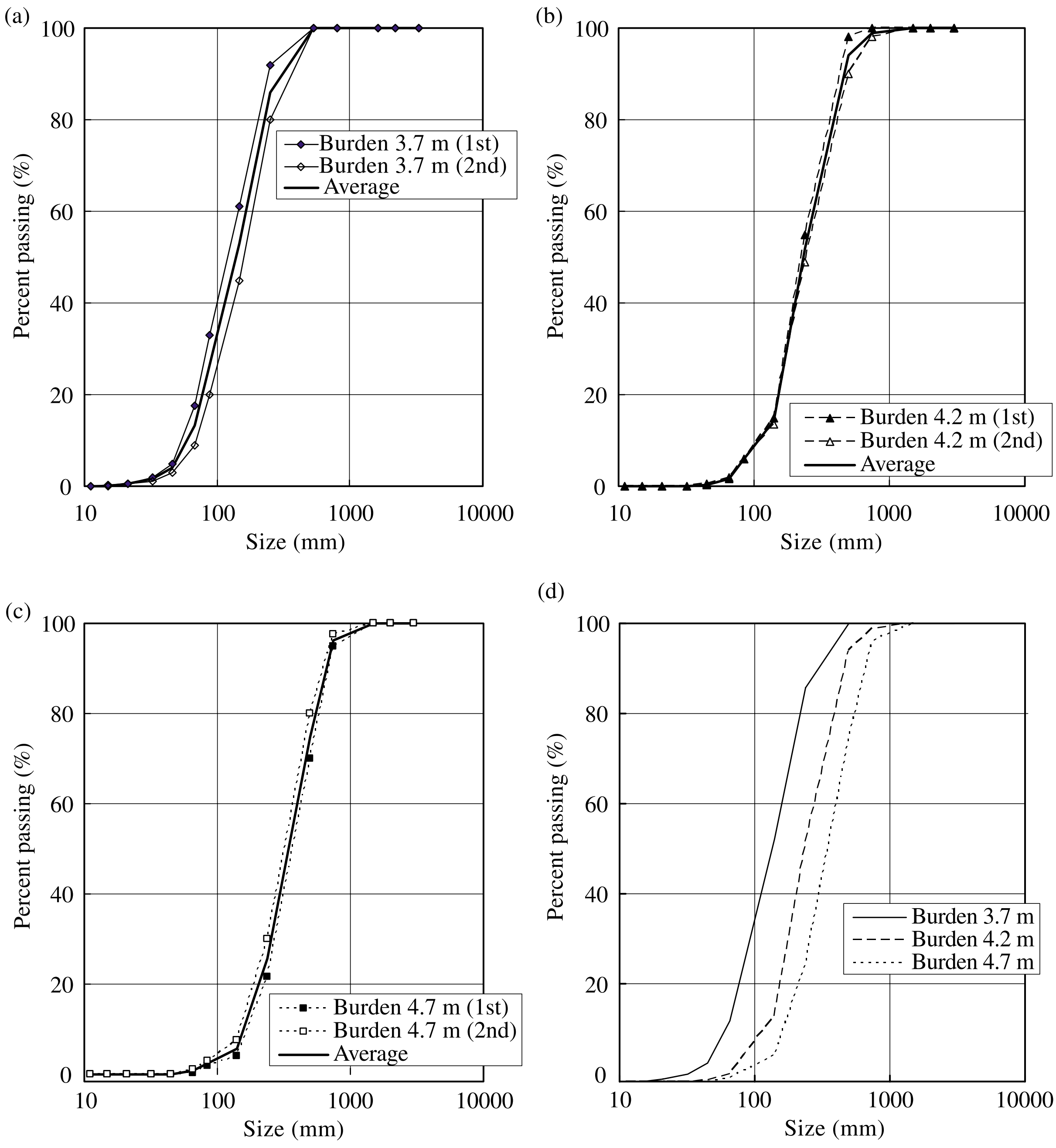

Fig. 8 Size distribution of the muckpile: (a) Burden 3.7 m; (b) Burden 4.2 m; (c) Burden 4.7 m; (d) All.

Table 4 Average fragment size (K_{50}) for specific burden.

Burden (m)	K_{50} (mm)
3.7	134
4.2	235
4.7	368

3.2 Fragmentation

Up to five photographs for each blasting operation had been taken from the muckpile. Typically, the muckpile is heterogeneous with respect to fragment size. Depending on the blast design, the largest sizes could be thrown the furthest from the blast, or they could slump down directly next to the blast. They may be some sort of gravitational segregation, where the fines are covering the larger blocks or alternatively the fines may have slipped in and behind the larger block. If assumption is made that the surface of the muckpile is representative, measurement can be simply a matter of personal decision by taking photographs of the muckpile at a number of blocks (photographing various cross-sections throughout the muckpile).

The five photographs from each muck pile were analyzed using software known as Split Engineering. The five photographs produced five results. The five results were then calculated to get one graph represent size distribution of one muckpile. Since blasting tests were managed in three scenario of burden, with each scenario consists of two tests, Fig. 8(a-c) represent size distribution of the muckpile resulted from blasting operations with burdens of 3.7 m, 4.2 m and 4.7 m respectively. Two size distributions within the same burden were found not exactly fit from one to another. The difference is reasonable since the blasting tests were carried out in heterogeneous rock mass. To be used in further analysis, two distribution sizes from two blasting tests with specific burden were calculated to get one distribution size represents blasted rocks of specific burden.

The differences of fragment size distribution resulted by blasting with specific burden are illustrated in Fig. 8(d). The figure qualitatively reveals that bigger fragments are produced by bigger burden. The phenomenon can also be described quantitatively by comparing the average fragment size (K_{50}) and the specific burden as presented in Table 4. This agrees with general consensus amongst blasting researcher that the average fragment size (K_{50}) increase with increasing burden[1)-3)]. The blasting tests showed that the relationship between the average fragment size (K_{50}) and burden (B) can be expressed by power law as $K_{50}=0.536B^{4.227}$ (Fig. 9). Note that K_{50} is specified in the order of millimeter, while burden in meter.

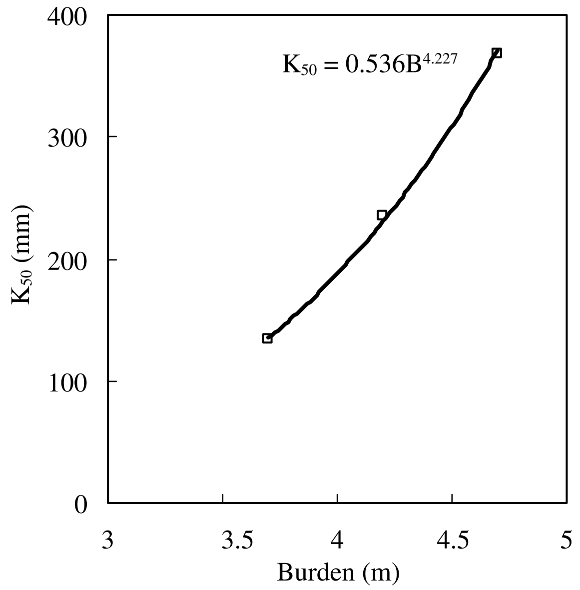

Fig. 9 Relationship between the average fragment size (K_{50}) and burden.

4. Conclusion

Blast vibration monitoring of three scenario of burden has been successfully done. The vibration monitoring results are in good agreement with what had been found by other researcher in terms of duration, amplitude, and frequency. Vibration waveforms typically last for 50 to 100 milliseconds. The peak amplitudes decrease according to additional distance. Frequencies decrease with increasing distance.

The weight scaling law between the PPV and scaled distance reveal three relationships for three different scenario of burden, which obviously indicate that blast burden influences vibration magnitude. The highest vibration magnitudes are produced by the biggest blast burden. Otherwise the lowest levels of vibration magnitudes are produced by the smallest blast burden. In simple words it can be said that vibration magnitude increase when the blast burden is increased.

Fragmentation measurement of muckpile using digital image also give plausible results. Using software known as Split Engineering, the fragmented rocks resulted from three scenario of blast burden can simply be calculated and presented in size distribution curve. The average fragment size (K_{50}; mm) increases exponentially with increasing blast burden (B; m) that can be expressed by K_{50}=0.536$B^{4.227}$.

In bench blasting, the optimum burden through the drilling pattern has been considered successful for controlling fragmentation. The present study has given another fact that rather than controlling fragmentation, the blast burden also influences vibration. When burden is designed bigger than its optimum value, blasting relatively results big fragmentation and consequently produce high vibration magnitude. Otherwise, when burden is designed smaller than its optimum value, blasting relatively results small fragmentation and consequently produces low vibration magnitude.

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