Article

Simulation of blast vibration controlled by delay blasting

Gento Mogi*†, Tsuyoshi Adachi*, Kouji Tamada*,
Ayano Ihara**, Tomoaki Arimatsu*, Hiroshi Kaburaki***,
Katsuhiro Eguchi***, and Yuji Ogata****

*The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
†corresponding author: gento@geosys.t.u-tokyo.ac.jp

**The University of Tokyo

**Recent affiliation: Boston Consulting Group, The New Otani Garden Court 4-1, Kioi-cho, Chiyoda-ku, Tokyo 102-0094, JAPAN

***Kawara-Taiheiyo Cement Co.Ltd., Kawara 812, Kawara-cho, Tagawa-gun, Fukuoka 822-1493, JAPAN

****National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba-shi, Ibaraki 305-8569, JAPAN

Received: March 1, 2004 Accepted: March 11, 2004

Abstract

Assuming that the vibration waves emitted by successive detonations in the near by holes, each having an identical set of explosives, are identical each other, a proper delay between holes, which significantly reduces the peak particle velocity (PPV) at any point of interest, can be designed, based on the theory of superposition of waves. Blast vibrations were measured in situ in order to design an efficient production blasting in an open pit limestone quarry, where the pit floor is approaching an abandoned stope whose roof must be maintained stable to prevent the pit floor from caving in. A relationship between PPV at the measuring point and the distance to epicenter was considered. Also PPVs based on different criteria, i.e. PPV minimization and auto-correlation minimization, were compared. Finally, two dimensional FEM analysis, based on the data of the in situ blast vibration measurements, was performed to estimate the distribution of the PPVs around a particular target point.

1. Introduction

Even though blasting is the most efficient means to fracture rock mass up to date and is commonly practiced in civil and mining enterprises world wide, ground vibration entailing the detonation of the explosives could cause problems to surface or even underground structures, if not controlled. Several blast vibration control techniques using delay blasting have been developed. From among those, sectional vibration control based on the theory of superposition of waves has been applied to several Japanese limestone quarries[1)-4)].

In case in which the vibration waves emitted by successive detonations in the near by holes, each having an identical set of explosives, could be assumed to be identical each other, a proper delay between holes can be designed which significantly reduces the peak particle velocity (PPV) at any point of interest. When designing a proper delay, the range, in which the PPV will be reduced below a critical level, should also be considered.

Several blast vibrations were measured at Kawara limestone quarry in order to design an efficient production blasting, where the horizontal level of the pit floor is approaching an abandoned stope for aragonite mining whose roof must be maintained stable to prevent the pit floor from caving in. Two dimensional FEM analysis by ANSYS, based on the data of the in situ blast vibration measurements, was performed to estimate the distribution of the PPVs around the measuring points.

2. Blast vibration measurement and analysis

2.1 In-situ measurement system

Vibration waves of bench blasting were measured at measuring points installed on the floor of the abandoned stope. All the waves were measured simultaneously at arbitrary two measuring points out of five, allocated in the same level as shown in Fig. 1. The vertical distance between the pit floor and the roof of the abandoned stope

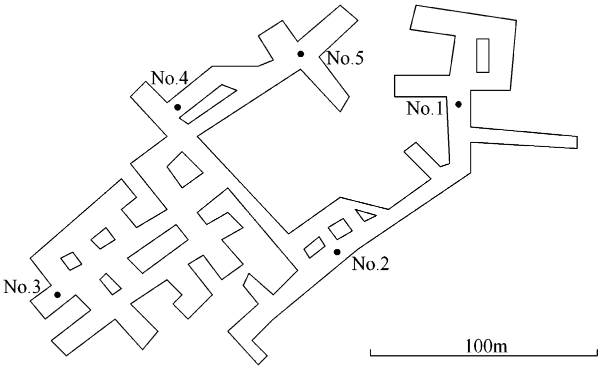

Fig.1 Measurement points.

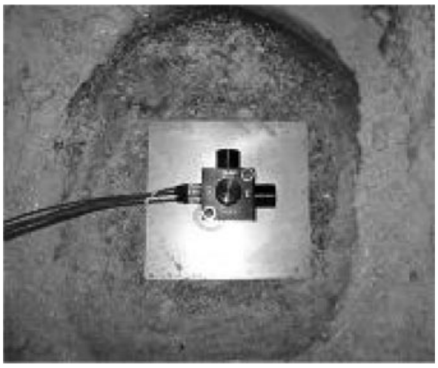

Fig.2 Tri-axial piezoelectric acceleration transducer.

Fig.3 Measurement system.

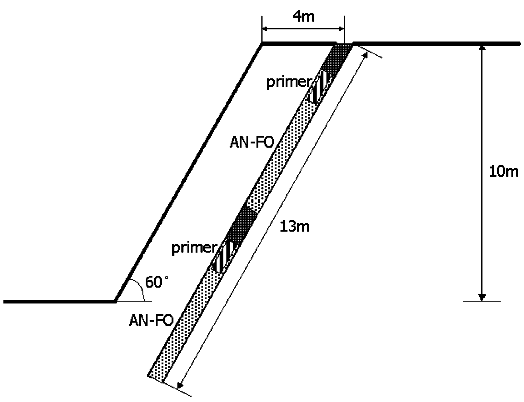

Fig.4 Bench geometry and blast hole design in the quarry.

at the time of measurements was ca.22m, so that careful blasting was needed to avoid scaling from the roof.

Tri-axial piezoelectric acceleration transducers (TEAC 707LFZ), which were fastened with bolts to an iron base fixed to the exposed intact floor rock by cement as shown in Fig. 2, were used as a sensor at each measuring point. The vibration wave signals from each transducer for three orthogonal directions were amplified by 200 to 1,000 times through a set of differential DC amplifiers (TEAC SA-25) and transferred to a data logger (GRAPHTEC DM3100) controlled by PC using LabVIEW. The measurement system except the transducers was installed in a shelter as shown in Fig. 3 to protect from scaling of the roof just in case.

2.2 Bench geometry and blast hole design

The bench height of the quarry is 10m. The diameter of the inclined blast hole (at 60deg.) for production blasting is either 95mm or 105mm, with a drilling length of 13m. AN-FO is used for a deck charge, as shown in Fig. 4, in combination with HAMAMITE as a primer and MS electric detonators.

2.3 Vibration wave data

Vibration waves of eleven blasting operations at several faces in the quarry were measured. Each operation is consisted by following shots. Two shots with an initiation time difference more than one second are regarded each other as an independent shot.

No.1, 28/10/2002:	7 ×single shots
No.2, 29/10/2002:	7 ×single shots
No.3, 31/10/2002:	6 ×double shots with 50ms delay
	triple shot each with 50ms delay
No.4, 01/11/2002:	2 ×double shots with 25ms delay
	2 ×double shots with 50ms delay
	2 ×double shots with 75ms delay
No.5, 18/11/2002:	6 ×single shots
No.6, 18/11/2002:	quadruple shot each with 25ms delay
	5 ×double shots with 130ms delay
	triple shot with 130 and 120ms delays
No.7, 19/11/2002:	3 deck charged holes,
	50ms deck delay and 25ms hole delay
	4 deck charged holes,
	50ms deck delay and 25ms hole delay
No.8, 20/11/ 2002:	2 ×double shots with 25ms delay
	2 ×double shots with 50ms delay
	2 ×double shots with 75ms delay
No.9, 20/11/2002:	5 deck charged holes,
	50-ms deck delay and 75-ms hole delay
No.10, 10/06/2003:	10 ×single shots
No.11, 11/06/2003:	10 ×single shots

The blasting No.1 was measured at measuring points No.2 and No.5. The blasting No.2 was measured at measuring points No.3 and No.4. All other blast vibration waves were measured at measuring points No.4 and No.5. The distance between measuring points No.4 and No.5 is 60m.

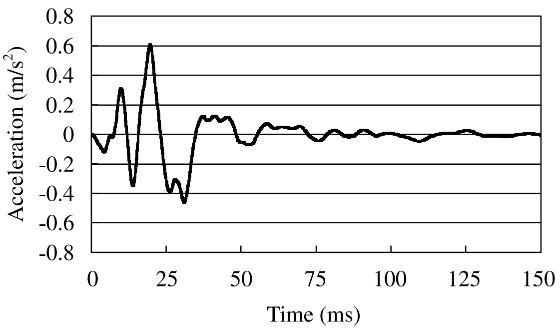

Fig.5a Measured acceleration wave of a single shot.

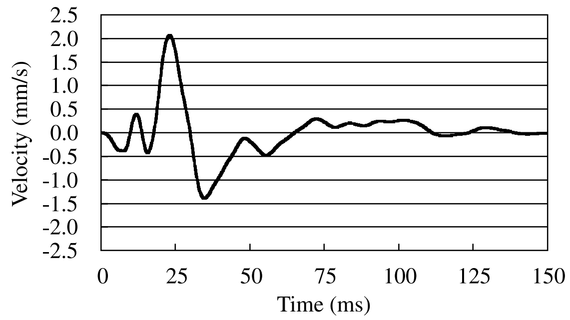

Fig.5b Calculated velocity wave of a single shot.

An example of blast vibration acceleration wave of a single shot, in which both decks in a hole were detonated simultaneously, is shown in Fig. 5a. By integrating the acceleration by time, velocity wave shown in Figure 5b is obtained.

2.4 Relationship between distance and PPV

Due to geometric and inelastic wave attenuation, PPV of the same blast vibration wave generally tends to decrease according to the increase of the distance from the epicenter. The relationships between 20 PPVs of composite particle velocity waves for three orthogonal directions from blasting No.10 and No.11 at measuring points No.4 and No.5 and each distance form the epicenter are shown in Fig. 6a and Fig. 6b, respectively. In blasting No.10 and No.11, approximately 40kg of AN-FO was charged in each hole. The horizontal location of the face for blasting No.10 and No.11 is shown in Fig. 7.

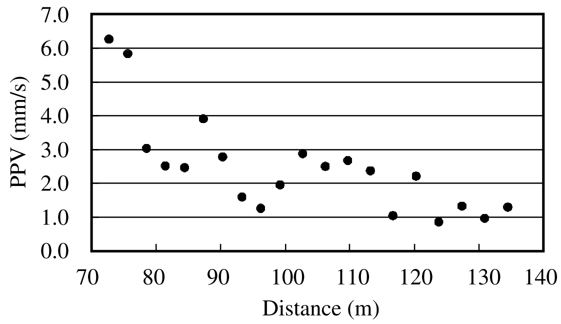

Fig.6a Distance and PPV at measuring point No.4.

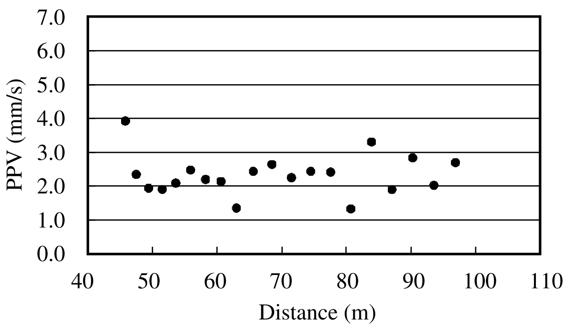

Fig.6b Distance and PPV at measuring point No.5.

As it is obvious from Fig. 6a, PPV gradually decreases according to the increase of the distance to each epicenter at measuring point No.4. Whereas at measuring point No.5, it seems as PPV does not depend on the distance.

The peak velocities of the vertical component of vibration waves reaching the measuring point No.5 in blasting No.10 and No.11, especially those from the nearer part of the face, were apparently smaller or the timing of its occurrence delayed compared to those for other two orthogonal directions. We could not identify the reason so far but it could be possible that the waves were disturbed either by some fractured zone or inhomogeneous rock mass with lower Young's modulus, existing somewhere in the path, or simply by the geometry of the stope.

2.5 Relationship between distance and optimum delay

Both, PPV minimization[1] and auto-correlation minimization[3] were adapted as the criteria to obtain the optimum delay for a two shots delay blasting based on particle velocity wave data of the corresponding single shot. Figure 8a shows the relationship between the distance from the epicenter and two kinds of optimum delays, obtained under above criteria in the range up to 30ms, for 20 single shots in blasting No.10 and No.11 at measuring point No.4. Those for measuring point No.5 is shown in Fig. 8b.

The correlations between the two optimum delays for measuring points No.4 and No.5 are 0.82 and 0.49, respectively. Considering that some of the waves arriving to measuring point No.5 could be disturbed, we can expect that in relatively homogeneous environment both criteria could come up with a similar optimum delay.

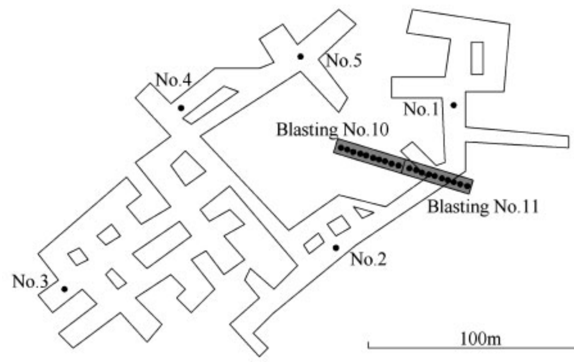

Fig.7 Horizontal location of blasting No.10 and No.11.

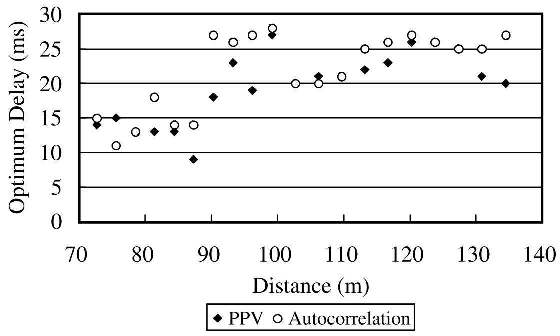

Fig.8a Relationship between distance and optimum delay at measuring point No.4.

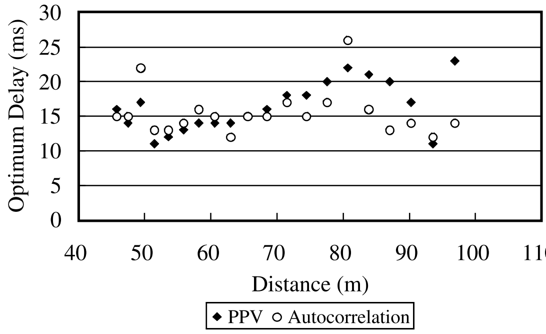

Fig.8b Relationship between distance and optimum delay at measuring point No.5.

3. Dynamic rock mass properties

3.1 Compressive wave velocity

Average wave propagation velocity of the limestone in the quarry can be estimated using the difference in arrival time of the vibration wave between the measuring points. The average compressive wave velocity and its standard deviation obtained from thirteen successful shots in blasting No.5 to No.8 are 1896.8m/s and 145.9m/s, respectively. Because it is very difficult to determine the true initiation point of the wave signal if its amplitude is not large enough, and consequently could cause error in estimation, only those data of the blasts which were close enough to the measuring points were analyzed. Also only those data of the axis facing to the epicenter were used to exactly identify the compressive wave.

3.2 Q value

Q value is an index for inelastic wave attenuation which could be obtained by comparing the spectra of waves at different measuring points. The smaller the Q value the larger is the inelastic attenuation. The ratio of two spectra $R(X_1,\omega)$ and $R(X_2,\omega)$ at different measuring points X_1 and X_2 is expressed in following equation:

$$\frac{|R(X_1,\omega)|}{|R(X_2,\omega)|}=\left(\frac{x_2}{x_1}\right)\exp\left\{-(x_1-x_2)\left(\frac{\omega}{2VQ}\right)\right\} \quad (1)$$

where ω : angular frequency (rad/s)
X_1, X_2 : distances of X_1, X_2 from the epicenter (m)
V : compressive wave velocity (m/s)
Q : Q value

Converting equation 1 in terms of Q and frequency f (1/s), we obtain:

$$Q=\frac{(x_2-x_1)f\pi}{\log\left(\frac{R(x_1,f)}{R(x\ ,f)}\right)\frac{x_1}{x_2}V} \quad (2)$$

Comparing the average spectra of six single shots in blasting No.1, which was done in the nearest face and sufficiently large signal could be measured at two measuring points No.2 and No.5, for eight major frequency components, eight Q values were obtained. The average and the standard deviation of those eight Q values are 11.8 and 9.2, respectively. Even though the Q values vary widely, the average value seems to be relatively reasonable compared to the reference data of 40 for an intact limestone core sample.

4. Numerical analysis

As it is widely recognized, the effective area of blast vibration control based on the theory of superposition of waves is limited to certain extent. From the aspect of a damage prevention of particular structure, it is essential to know the distribution of the PPVs around the target point. Numerical analysis, using the two dimensional FEM code of ANSYS, has been performed to evaluate the effective area in which PPV is controlled within a certain level.

4.1 Two dimensional model of the stope

Vertical cross section including the measuring point No.5 and a blast hole in blasting No.11 was considered as a model for the two dimensional analysis. The dimension of the model is shown in Figs. 9a and 9b.

Horizontal pressure wave simulating the wave caused by detonation was applied from the right hand side of the model to a 1m long vertical boundary beneath the pit floor

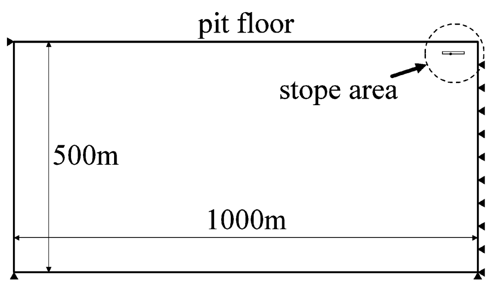

Fig.9a Overall dimension of the model.

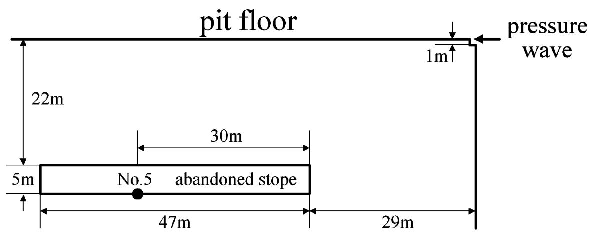

Fig.9b Dimension of the stope area and the measuring point.

at the upper right corner of the model. The horizontal distance of the boundary from the epicenter, which is the bottom part of the hole drilled from the bench down into the pit floor, is 1m, a distance that is assumed far enough to remain undamaged by detonation.

4.2 Parameters for the analysis

Young's modulus:	3.7_103 (MPa)
Poison's ratio:	0.13
Specific gravity:	2670 (kg/m3)
Attenuation parameter:	0.0006

Young's modulus of the rock mass was decided to yield an average compressive wave velocity in the model within the range of 1,500m/s to 2,000m/s, under fixed Poisson's ratio and specific gravity of the Kawara limestone. Inelastic attenuation parameter was set so that the calculated Q value from the attenuation of a simulated wave in the model becomes ca. 10.

4.3 Pressure function

Pressure wave of a blast around the epicenter is generally expressed in following function.

$$p(\mathrm{t}) = P_0 \xi \{ \exp(-at) - \exp(-bt) \} \qquad (3)$$

where P_0: Maximum pressure (MPa)

ξ, a, b: Constants

Considering the detonation velocity of AN-FO and the charge length, the pressure build up time was set to 4ms. From the measured vibration waves, the duration of the detonation pressure was estimated to be ca.100ms. Consequently, following pressure function was used for simulation.

$$p(t) = 3 \times \{\exp(-100t) - \exp(-500t)\} \text{ (MPA)} \qquad (4)$$

The relationship between the time and pressure applied to the boundary according to the above function, representing the detonation of explosives in the bore hole, is shown in Fig. 10.

4.4 Verification of the parameters

To verify the determined parameters, a single shot in blasting No.11 was simulated. The calculated horizontal vibration velocity wave at measuring point No.5 is shown in Fig. 11a. The corresponding horizontal vibration velocity wave calculated from the measured horizontal acceleration wave of blasting No.11 at measuring point No.5, is shown in Fig. 11b. By comparing both Figs. 11a and 11b, we can conclude that the vibration wave is reproduced with a satisfying accuracy.

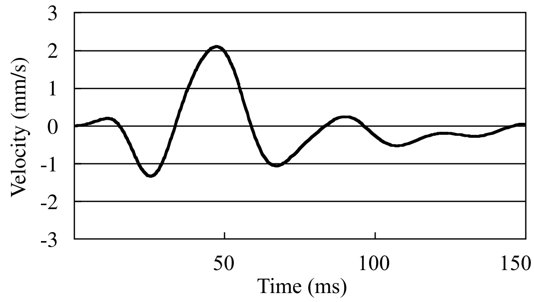

Fig.11a Simulated horizontal particle velocity wave.

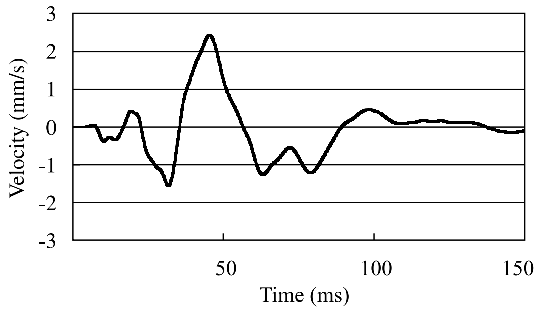

Fig.11b In-situ horizontal particle velocity wave.

4.5 Simulation of delay blasting

A two stage delay blasting was simulated using the model. Even though the optimum delay for two stage blasting, which minimizes the PPV at measuring point No.5, calculated from the measured vibration wave was 16ms, 25ms delay blasting was simulated as 25ms is the minimum delay of a standard MS-detonator.

Figure12 shows the applied pressure wave function for 25ms delay blasting simulation. Horizontal PPVs at several points on the floor of the stope were obtained, first for single shot and then also for two stage delay blasting. The relationship between the PPV and the horizontal location in the stope is shown in Fig. 13. Those black dots in Fig. 13 are PPVs at the measuring point No.5. The horizontal distance of the left hand side boundary of the stope from the epicenter is 76m, and that of the right hand side boundary is 29m. PPV in general is decreasing according to the increase of the horizontal distance, but in those points

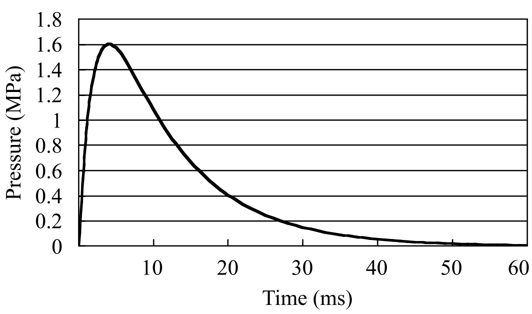

Fig.10 Pressure function.

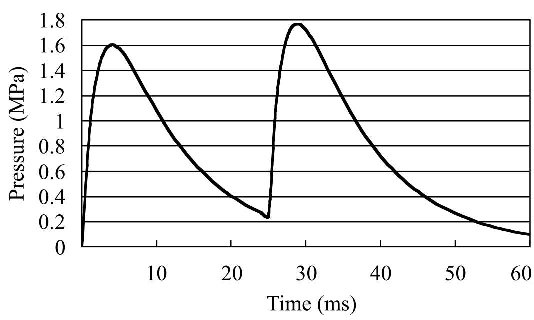

Fig.12 Pressure wave function for 25ms delay blasting.

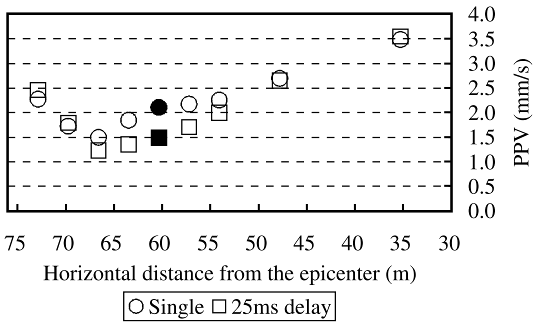

Fig.13 PPV distribution on the floor of the stope.

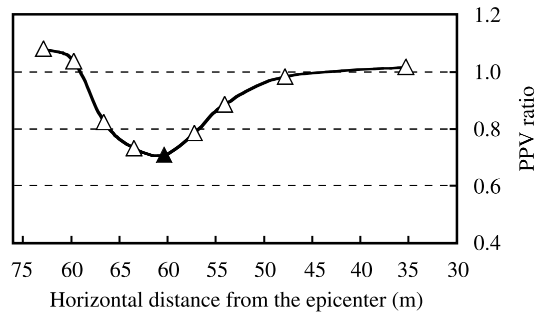

Fig.14 Distribution of the horizontal PPV ratio.

close to the left hand side boundary of the stope, it tends to increase while the distance from the epicenter increases, probably due to the influence of the boundary.

According to the simulation results, horizontal PPV of the 25ms delay blasting at measuring point No.5 was reduced to 71% of that of comparable single shot. Distribution of the ratio of horizontal PPV between two stage delay blasting and single shot, along the floor of the stope, is shown in Fig.14. It is clearly seen that due to proper delay, PPV has been efficiently reduced on the floor of the stope within the range from 50m to 70m in horizontal distance from the epicenter. Because scaling tends to occur in particularly limited areas where rock condition is apparently worse than surrounding rock mass, vibration control by appropriate delay, targeting the center of such area, could be effective.

5. Conclusion

The relationships between 20 PPVs of composite particle velocity waves for three orthogonal directions and each distance form the epicenter were obtained for two measuring points. At one point, a gradual decrease in PPV according to the increase of the distance from the epicenter was observed, while at the other point, PPV did not correlate with distance due to unknown disturbance of the vertical vibration waves.

PPVs based on different criteria, i.e. PPV minimization and auto-correlation minimization, were compared and relatively high correlation was observed at an undisturbed measuring point.

Two dimensional FEM analysis, based on the data of the in situ blast vibration measurements, was performed to estimate the distribution of the PPVs around a target point. In this case, a possibility is shown that the PPV could well be controlled within approximately 20m range around the target point.

References

1) G. Mogi, et. al., Consideration on local blast vibration control by delay blasting, Journal of the Japan Explosives Society, Vol.60, No.5, pp.233-239 (1999).
2) G. Mogi, et. al., Reduction of blast vibration by means of sequentially optimized delay blasting, Explosive & Blasting Technique, Proceedings of the 1st World Conference on Explosives and Blasting Technique, (Munich), pp. 219-224, 6-8 September (2000).
3) Y. Wada, et.al., A study on the control of vibration caused by a blasting, Journal of the Japan Explosives Society, Vol.55, No.4, pp.174-180 (1994).
4) M. Yamamoto, et. al., Theoretical study on blast vibration control method based upon wave interference, Journal of the Japan Explosives Society, Vol.59, No.5, pp.221-240 (1998).

段発発破による発破振動制御のシミュレーション

茂木源人*†，安達 毅*，玉田康二*，伊原彩乃**，
有松知朗***，鏑木寛****，江口克洋****，緒方雄二*****

香春太平洋セメント(株)香春鉱山において発破振動の現場計測を行ない，計測点における最大変位速度（PPV）と震源までの距離との関係を考察した。また，段発発破の際の最適な遅れ秒時を２種類の規準により求め，結果の比較を行なった。さらに，現場計測の結果に基づき2次元FEMモデルのパラメータを決定し，段発発破を含む発破振動の数値シミュレーションを行なった。段発発破に関しては，薬量が等しい各発破孔間に任意の遅れ秒時を設定した発破において，各孔から発生する振動波を同一なものと見なし，目的地点近傍の各節点の振動からPPVの分布を求めた。その結果，最適遅れ秒時を用いた段発発破による局地的振動制御の有効範囲を推定することが可能となった。

* 東京大学大学院工学系研究科地球システム工学専攻　〒113-8656 東京都文京区本郷７−３−１
†corresponding author: gento@geosys.t.u-tokyo.ac.jp
** 東京大学工学部システム創成学科知能社会システムコース，現ボストン・コンサルティング・グループ
*** 東京大学工学部システム創成学科知能社会システムコース
**** 香春太平洋セメント（株）
***** 独立行政法人産業技術総合研究所