Control of Blasting Ground Vibration Near Grouting Operations (Case Study)

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Abstract

Before the embankment of the dam body, grouting curtain for eliminating all discontinuities in the areas of foundation of dam and the access to the curtain conditions in accordance with the technical specifications is down. The drilling and blasting techniques usage for excavation of rock under the dam foundation for achieve non-weathered bedrock. It is common that vibration-inducing operations such as excavation occur concurrently with grouting or after grouting, has been conduct. Ground vibrations are an integral part of the process of rock blasting and consequently they are unavoidable and the amount of vibration increases with increasing explosives. Non-control of blast vibrationcan have a detrimental effect on the quality of the grouting operation because of the performance of the curtain. A wide range of peak particle velocity are calculated based on the strength of the grout, which changes with time, and the mix type, since thicker grouts have lower WCRs (water-to cement ratio) and therefore higher strengths. In order to control the vibration of the blasting operation the amount of charge per delay, delays condition and the amount of explosives consumed at each explosion should be determined and controlled. In this paper, for a dam project, initially, seismographs measured the amount of vibration of the explosion. Then, based on the amount of allowable vibration recommended by the latest edition of the manual USACE (GROUTING TECHNOLOGY 2017), the amount of charge per delay was determined.

Keywords: Blasting, Allowable Vibration, Grouting curtain.

1. INTRODUCTION

Drilling and blasting is an integral operation in any excavation project. This is largely due to the fact that fragmentation of rock using explosives is much more economical over other existing techniques. However, energy of an explosive cannot be fully utilized for fragmentation and displacement of in-situ rock mass only. A large part of explosive energy dissipates as uncontrolled ground vibration, air blast, back-break or over break and fly rock. Among these, back-break or over break is termed as blast induced damage to surrounding rock and is the main concern of this present research. Damaged rock due to blasting causes a number of problems, viz. (i) drilling to the next blast round becomes critical, (ii) chances of eruption/ejection of explosive energy in uncontrolled manner leading to poor fragmentation during next blasting and also the chances of fly rock, (iii) increase in support cost (for underground opening) and many more. Thus, it is felt to assess the extent of rock damage due to blasting, which is considered as a function of peakparticle velocity (PPV).

2. PRINCIPLE OF FRAGMENTATION BY EXPLOSIVES

Understanding the basic principles of rock fragmentation by explosive charges is crucial for ground vibration assessment and optimizing successful blasting operation). 1-20% of the energy of a detonated explosive charge, and 5-15% transferred to the surrounding rock as shock waves. The remaining part of the explosive energy released as very high pressure and temperature gaseous products of the reaction. Only a fraction of explosive energy (20-30%) used in the actual breakage and displacement of the rock mass, and the rest of the energy is spent in undesirable effects like ground vibrations, fly rocks, noises, back breaks, over breaks, etc. There are three zones of varying destruction and deformation around the explosion. These zones are (i) the strong shock zone or hydrodynamic zone (ii) the non-linear zone, and (iii) the elastic zone. In the first zone, the radial compressive stresses generated from the shockwave exceed the dynamic compressive strength of the surrounding rock, and develop complete crushing as rock fail in compression, Figure 1. In the second zone, fracturing is due to the tangential stress. Since the tensile strength of the rock is not very high, the tangential tensile stresses create fractures. When the strain wave reaches the free surface of the rock, it is reflected and may cause spalling.

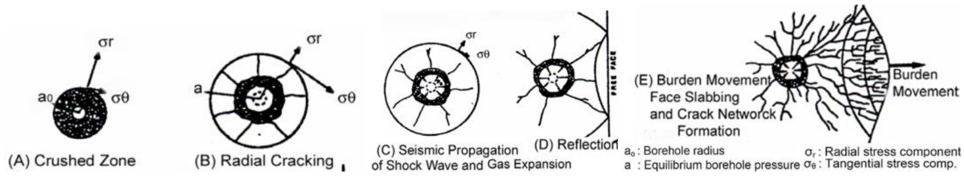

Figure 1. Sequence of events occurring in the rock mass after detonation

In the crushed zone immediately around the borehole, the explosive-induced pressures and stresses exceed the dynamic compressive strength of the rock by factors ranging from 40 to 400. These high pressures acting against the borehole wall will crush, pulverize, and shatter the surrounding rock mass causing intense damage. This zone is also referred to as the hydrodynamic zone in which the elastic rigidity of the rock becomes insignificant. Next to the crushed zone is a region defined by a severely fractured zone referred to as the nonlinear zone. Here fracturing can range from severe crushing, through partial fracturing, to plastic deformation. Extension of cracks can occur from previously formed crack by the tangential component of the shock wave, from infiltration of gas pressure, and at flaw sites. In zones 3 and 4 (elastic zones), tensile failures and crack extensions occur in a less intense mode, because the stress wave amplitude has attenuated significantly (much of the original energy from the detonation has been consumed in the form of heat, friction, and fracturing in zones 1 and 2). The peak amplitude of the compressive stress is now much smaller than the compressive strength of the rock, so no new fractures are likely in this wave type. However, the tangential stress component of the wave is still substantially larger than the tensile strength of the rock. This stress is large enough to cause radial fractures. In zone 5 the individual particles of the medium will oscillate and vibrate about their rest positions within the elastic limits of the rock so no permanent damage results. It is this region where seismic waves are carried considerable distances and are responsible for ground vibrations. (Figure 2.)

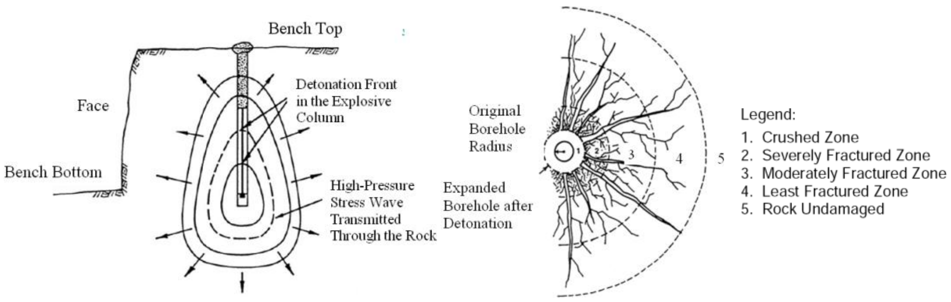

Figure 2. Section through face during detonation showing expanding stress wave front and Zones of rupture radius

Since the velocity of longitudinal waves is larger than the velocity of shear waves and as the strength of the rock in tension is much less than in compression, the reflected wave will break the rock in tension if it exceeds the tensile strength. After the passage of the wave, the expanding explosion products start to penetrate into the radial cracks and exert high quasi-static pressure. High temperature and high-pressure borehole explosive gases can then flow into the system of the radial cracks generated and cause considerable additional extension of the number of these cracks. As the burden begins to move high compressive stresses within the rock begins to unload and generate more tensile stresses which complete the fragmentation process. The rock fracture during blasting is caused by the combined effects of shock and gas energies of an explosive and gas energy plays a relatively higher role during rock fragmentation depending upon the energy partitioning characteristics of the explosive. The remaining shock energy (spent after that rock fracturing) from the blast, in the absence of free faces travels as seismic waves in the ground.

3. TYPES OF VIBRATION WAVES

Interactions between the vibrations and the propagating media give rise to several types of waves. The main wave types can be divided into two varieties, body waves and surface waves. Body Waves include Primary (P) Wave, compression & vibrates parallel to direction of movement. Fastest seismic wave, and Secondary (S) Wave, known as a shear wave, vibrates perpendicular to the P Wave. Only travels in solids. Surface Waves include Rayleigh (R) Waves, Behaves like water waves with an elliptical motion and Love (L) Waves, Shear motion in a horizontal plane, therefore most destructive & fastest of the surface waves. Body waves travel deepest and are usually of relatively small amplitude and high frequency as compared to the surface waves. Surface waves generated from blasting are formed by the interaction of seismic energy and the surface of the earth or other near-surface geologic features. They propagate more slowly than body waves and travel through the uppermost geologic layers. These waves we will show using 3-D geometry for area of a elastic deformation; of course, when strength of wave is greater than elastic limit of material a plastic deformation is formed. Surface waves produced from blasting often contain the peak particle-velocity (PPV) phase - the part of the vibration waveform having the highest amplitude. (Figure 3.)

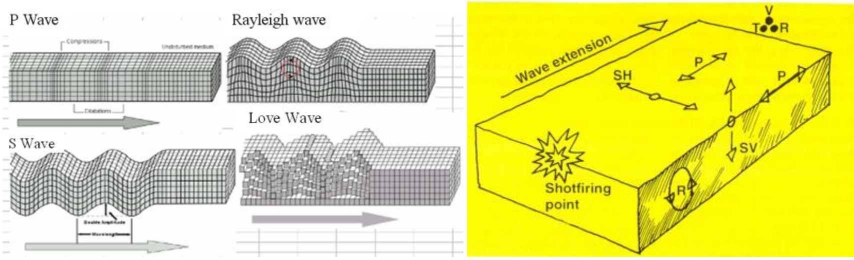

Figure 3.Comparison of body and surface waves

4. BLASTING & VIBRATIONS

Ground vibrations due to rock blasting are one of the important aspects that must be considered and often it is necessary to show that the ground vibrations due to a project will not damage nearby structures in order to receive needed permissions for such projects. While it is possible to control the level of vibrations by choosing the right techniques the economical aspects of the project usually requires as high maximum delay weight as possible. Therefore, it is desirable to be able to make good predictions on the maximum allowed charges in early stages of the project. Numerous variables in vibrations contribute to the complexity of the problem. The variables of interest in evaluating vibration problems include (1) the amount of energy causing the vibration, (2) the range of distance from the source to the point of interest, (3) the attenuation properties of the ground conditions, (4) the frequencies of the vibration, (5) the natural frequency of the structure at the point of interest, and (6) the corresponding acceleration, velocity, amplitude, and strain by induced by the vibration at the point of interest.

5. PEAK PARTICLE VELOCITY

Since many of the vibration, variables are related, and for simplification purposes, a maximum velocity is typically specified as a threshold for limiting damage. The velocity generally specified is the peak particle velocity (PPV), which is the vector sum of the velocities measured along three axes (radial, vertical, and tangential). The frequency of the vibration is an additional consideration. As vibration frequencies approach the natural frequency of a structure, resonance can occur, greatly amplifying the strain induced on the structure. Additionally, studies have indicated that lower-frequency vibrations may induce damage at relatively low PPVs, whereas structures may tolerate higher PPVs at higher frequencies. The simplest form of vibration is the simple harmonic movement, often called a sine (sinusoidal) vibration:

$$X(t) = A\sin(\omega t + \varphi) \quad (1)$$

Where A is the displacement amplitude, ω is the angular frequency, t is the time, and φ is the phase angle. For many practical applications, the phase angle has little significance. The vibration can then be characterized by two parameters: the amplitude and the frequency. At a given location, peak particle velocity depends on the distance from the blast and the maximum charge per delay. The DGMS Circular requires that square root scaling shall be used when blasting is carried out on the surface and vibrations are also monitored on the surface. The square root scaling to estimate PPV is given by:

$$V = K(D/\sqrt{Q})^{\beta} \quad (2)$$

where V is the peak particle velocity (mm/s), D is the distance between the blast and the monitoring station (m), Q is the maximum charge per delay (kg), and K and 'β' are the site constants. Typical K factors is shown in Table 1. β is slope of particle velocity-scaled distance data on a log-log plot (~is constant for each component at a site, but may vary from site to site). Conventionally, D/ Q is called scaled distance. Peak particle velocity is plotted against scaled distance on logarithmic scales. The site constants for a mine can be determined by regression analysis of the data sets. Particle velocity damage criteria for rock mass is shown in Table 2.

Table 1.Typical K factors

Rock Condition	K factor
Free face – hard or highly structured rock	500
Free face average rock	1140
Heavily confined	5000

Table 2. Particle velocity damage criteria for rock mass

Particle Velocity	Damage Criteria
10 in/sec(254 mm/sec)	no fracturing of intact rock
10-25 in/sec(254-635 mm/sec)	minor tensile slabbing will occur
25-100 in/sec(635-2540 mm/sec)	strong tensile & some radial cracking
100 in/sec(2540 mm/sec)	complete breakup of rock mass will occur

variables, which have an effect on either the intensity or the character of the vibrations include maximum charge weight detonating at one time, true distance (distance the waves must travel), geological conditions, confinement, physical properties of the rock, coupling, spatial distribution, detonator, timing scatter, time of energy release and type of explosive. The equation (3) relates the tensile stress of concrete to the maximum PPV that will induce cracking:

$$v = \sigma/\rho c \tag{3}$$

where v = particle velocity for failure, fps. σ = failure tensile strength, psi. ρ = mass density, lb sec2/ft4. c=propagation velocity, fps. Can also be defined as:

$$\sigma_t = \rho \times c \times u \tag{4}$$

where σt = allowable tensile strength (taken as 10% of the unconfined compressive strength), lb/ft2. ρ = mass density = 150 lb/ft3. c = seismic velocity of concrete, taken as 10,000 ft/s. u = maximum particle velocity, ft/s.

6. Vibration Control Near Grouting Operations

Vibrations near grouting applications can be a consideration on certain projects. It is not uncommon that vibration-inducing operations such as excavation occur concurrently with grouting or after grouting has been conducted. While little information is available regarding tolerable vibration levels for grout, a significant amount of information, including guidelines, is available for tolerable vibrations in the vicinity of concrete and various types of structures. Vibrations can be divided into three subcategories: Transient, Steady-State, and Pseudo-Steady-State. Transient vibrations are single events. The vibration decreases rapidly with time. Examples include vibrations induced by impact pile driving and blasting. Steady-state vibrations occur continuously. The magnitude of the vibration is generally constant with time. Examples include vibrations induced by vibratory pile driving equipment and large, stationary machinery. Pseudo-steady-state vibrations are relatively random in nature. The magnitude of the vibration varies with time. Examples include vibrations induced by impact hammers and large excavation equipment.

7. Established Thresholds

Very limited information exists with regard to tolerable vibration limits for grout or grouted structures. However, given the ever-increasing prevalence of grouting in construction and new methods using grouting materials (jet grouting, soil mixing, etc.), it is an important consideration. The allowable extent of vibration depends on the purpose of the grouting application (e.g., seepage control, structural support, reduction of discontinuity volume), the ability or lack thereof to physically inspect areas where damage may occur, and the costs of remediation if damage were to occur. In applications such as dam foundation grouting, the grout is placed with the intent of eliminating all discontinuities. Cracking and displacement of grout placed into discontinuities are obviously undesirable in seepage control applications. If extensive vibration damage were to occur, the level of effort required to fully investigate and remediate the damage may equal the original cost of the curtain itself. In contrast, drilling and blasting techniques are common in the tunneling industry, and in many cases, grouting in advance of blasting is conducted at the face. Given the proximity of the grouted zone to the blasting, it is obvious that large vibrations are induced in locations where grout has been recently injected. However, in this application, the consequences of vibration damage may be minimal in that one of the primary functions of the grout is to fill spaces between rock blocks to prevent movement, and cracking of the grout would not impair that function.

Further, if the tunnel grouting also has a flow control function, any leakage into the tunnel as a result of blast damage is directly observable and can be remedied at minimal cost and effort. Potential problems in tunnel applications can also be reduced by using high-strength grouts and accelerators and by grouting multiple excavation rounds forward of the face. Assuming that tolerable vibrations for grout are proportional to those for concrete with respect to unconfined compressive strength, it is apparent that the strength of the grout may be an important consideration when specifying maximum PPVs. When grouting techniques induce mixing of grout with native materials, such as in soil mixing and jet grouting, the strength of the resulting mixed mass is likely to be more important than the strength of the grout itself.

Table3. Shows a range of unconfined compressive strengths from balanced stable grouts for a recently constructed grout curtain. Table4. Lists the calculated range of u values (maximum particle velocities) obtained. As can be seen, a wide range of PPVs are calculated based on the strength of the grout, which changes with time, and the mix type, since thicker grouts have lower WCRs and therefore higher strengths. Even at 28-day strengths, the thinnest grouts may crack when subjected to PPVs in excess of 2 in./s using the above criteria.

Table 3. Range of unconfined compressive strengths for various balanced stable grouts

	Compressive Strength (psi)							
Mix type	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G+	Mix G
3-day	160	195	240	375	475	750	810	915
7-day	190	265	430	595	725	1005	1100	1175
14-day	365	380	510	820	1060	1285	1410	1455
28-day	420	535	735	1070	1490	2560	2395	2755

Table 4. Range of calculated maximum particle velocities for grout using the above equation derived

	Calculated Max. Particle Velocity (PPV) in in./s from EM 1110-2-3800							
Mix type	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G+	Mix G
3-day	0.9	1.1	1.3	2.1	2.6	4.2	4.5	5.1
7-day	1.1	1.5	2.4	3.3	4.0	5.6	6.1	6.5
14-day	2.0	2.1	2.8	4.6	5.9	7.1	7.8	8.1
28-day	2.3	3.0	4.1	6.0	8.3	14.2	13.3	15.3

8. Recommendations Specific to Vibrations and Grouting

Whenever possible, it is preferable that no blasting be allowed until at least 3 days after any injected grout has taken initial set. The reason for this recommendation is twofold. First, blast waves may induce high pore-water pressures in groundwater. These pore pressures may result in movement and shifting of the unset grout, causing windows and defects in the curtain. Second, it minimizes the potential damage to the grout, since the grout will have obtained some nominal minimum strength before the blast. In the absence of other information, a maximum allowable Peak Particle Velocities of 0.5 in./s as measured at the point of the grouting application is recommended.

9. Description Of Site And Rock

This project is embankment dam in west of Iran. Before the embankment of the dam body, grouting curtain for eliminating all discontinuities in the areas of foundation of dam and the access to the curtain conditions in accordance with the technical specifications is down. In this project for excavation of areas of foundation dam, need to blast. Vibrations were recorded in Limestone and Tuff quarry. The tuff is grey or cream in color, hard, compact, low porosity and medium density. Massive and fined grained. It is jointed, filling with clayey material encountered along the joint planes with UCS=88.8 MPa. Limestone is fine grained, massive, hard, high density and low porosity, compact and microcrystalline, with UCS=86.1 MPa.

10. Results of the Measurement Ground Vibration

Blasting seismographs are deployed in the field to record the levels of blast-induced ground vibration and air overpressure. For this study, ground vibrations were measured with two digital Vibraloc ABEM Instrument AB, is a full waveform Blast Vibration Monitor with an integrated tri-axial geophone system. Vibraloc is capable of storing about 1000 events (1000 Hz sampling rate and 1 second recording length). The instrument is designed to give a total +/-5% accuracy of the sampled values in the range 15-250 Hz and 1 –240 mm/s when using the internal geophones. (2%, 1-250 Hz excluding the geophone). In addition, the instrument is designed to give +/-2% accuracy in the range 1-250 Hz and 0,5-150 Pa excluding the microphone (Figure 4).

For blasting usage of drill holes diameter 64 mm, depth 4-6 m, Burden 2m and use of main charge ANFO(Ammonium Nitrate Fuel Oil), booster and shock tube NONE-system (non-electric delay detonator)(Figure 5.). Results of this study, amount of explosive per delay of blasting operations and vibration measurement (peak particle velocity, frequency etc.) oscillations velocity diagrams are showing in Table 5, and Figure 6.

Figure 4. digital seismograph/ Installation and arrangement

Figure 5. View of dam area befor\after blasting

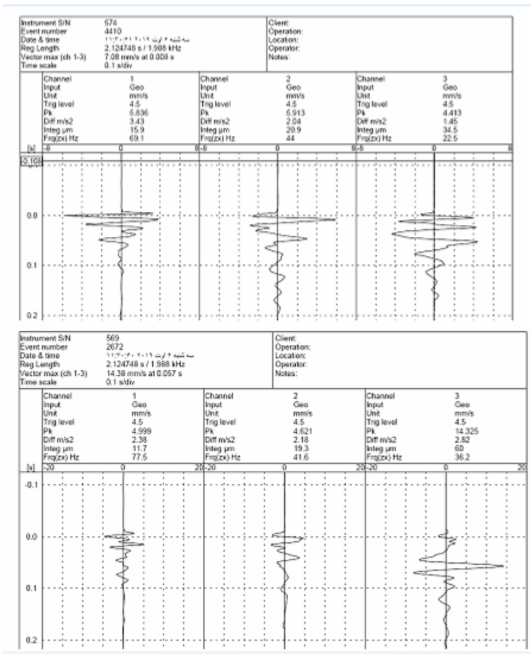

Figure 6. Characteristic oscillations velocity diagrams

Table 5. Seismic data summary for the blast

No	Maximum charge in One Delay Time	Blasting Distance	PPV mm/sec (Transverse/Longitudinal/Vertical)			PPV (max)	Frequence(HZ) (Transverse/Longitudinal/ Vertical)		
	kg	m	V	L	T	mm/sec	V	L	T
1	5.4	57.0	6.5	6.2	3.4	8.0	6.5	7.1	3.4
2	5.4	55.0	2.5	2.7	5.5	6.6	8.6	2.6	18.0
3	3.7	52.0	5.0	3.1	7.1	9.2	7.4	12.0	1.6
4	5.4	49.0	8.3	6.6	5.4	11.9	38.0	5.5	10.0
5	5.4	46.0	5.6	6.3	3.4	9.1	34.0	83.0	75.0
6	5.4	43.0	10.0	7.7	9.6	15.9	17.0	71.0	55.0
7	5.4	41.0	3.6	3.6	4.4	6.7	88.0	73.0	61.0
8	11.40	28.0	19.7	22.2	6.4	30.4	18.0	32.0	35.0
9	10.40	31.0	21.3	12.3	4.9	25.1	18.0	28.0	28.0
10	8.40	42.0	6.5	6.2	3.4	9.6	27.0	23.0	15.0
11	7.40	45.0	4.8	5.1	3.3	7.7	24.0	24.0	19.0
12	11.40	32.0	21.3	15.3	7.3	27.2	30.0	28.0	25.0
13	10.40	35.0	15.6	14.0	8.8	22.7	27.0	24.0	23.0
14	9.40	41.0	8.1	7.3	4.9	12.0	28.0	25.0	23.0
15	8.40	46.0	6.2	6.6	3.3	9.7	29.0	21.0	21.0
16	7.40	49.0	6.2	4.2	2.0	7.7	30.0	19.0	20.0
17	8.80	38.0	14.0	17.4	9.0	24.1	34.0	31.0	22.0
18	2.90	44.3	4.0	7.2	4.9	7.7	48.7	37.8	33.5
19	2.90	37.4	7.8	9.4	8.1	10.0	46.9	33.5	46.9
20	3.40	36.2	14.8	11.9	8.7	16.6	94.6	48.2	84.2
21	3.40	45.2	6.1	5.2	6.1	11.6	69.8	65.1	32.9
22	4.40	48.3	5.8	5.9	4.4	7.1	69.1	44.0	22.5
23	4.40	42.8	5.0	4.6	14.3	14.4	77.5	41.6	36.2
24	4.90	35.7	21.5	8.8	14.5	22.6	98.2	33.6	74.9
25	4.90	37.0	11.5	8.9	13.5	17.0	71.5	28.0	23.8
26	4.15	45.2	3.6	4.0	7.5	7.5	62.3	34.2	34.7
27	3.90	43.3	5.6	8.2	5.0	9.6	67.9	51.6	67.0
28	3.90	39.1	4.2	4.3	6.4	6.5	42.1	45.7	43.0
29	3.40	45.3	6.1	5.2	6.1	11.6	69.8	65.1	32.9
30	3.40	41.3	3.6	3.6	11.3	6.4	37.3	35.2	41.1

The particle-velocity waveforms were recorded from 15 of the production blasts, providing a total of 30 relationships between vibration levels, propagation distance, and charge mass, these data were fitted by means of regression analysis shown in Figure 6 to give the propagation equation:

$$PPV = 325.36(D/\sqrt{Q})^{-1.1605} \tag{5}$$

In the base of equation (5), constants K=325.36 and β= 1.1605 are computed.

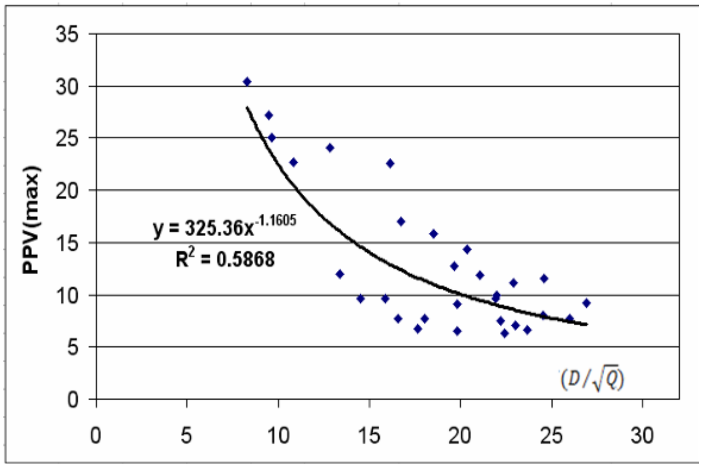

Figure 6. Relation charge per delay and the peak particle velocity

11. THE CHARGE PER DELAY AND OPTIMUM DELAY INTERVAL

In this project, unconfined compressive strengths of grout for 7-day and 28-day are 610 Psi and 1100 Psi similar to Mix-D in the Table 3. Therefore, Maximum particle velocities for unconfined compressive strengths for various balanced stable grouts 3, 7, 14 and 28-day are 2.1, 3.3, 4.6 and 6.0 in/sec. In the base of equation (5), in the Table 6 relation between blasting distance/unconfined compressive strengths for various balanced stable grouts and charge(ANFO) per delay for this case are computed.

Table 6. Relations blasting distance/unconfined compressive strengths and charge per delay

No	Blasting Distance (m)	Charge per Delay (kg)			
Unconfined Compressive Strength		3-day	7-day	14-day	28-day
Max. Particle Velocity(in/s)		2.1	3.3	4.6	6.0
1	50	3	8	17	29
2	75	7	19	37	65
3	100	13	33	66	115
4	125	20	52	104	180
5	150	29	75	149	260
6	175	40	101	203	354
7	200	52	133	265	462

In addition, the millisecond delay interval can be found from the average value of predominant frequency calculated using FFT method (Fast Fourier Transform). However, it is well known that pyrotechnic detonators have a certain scatter in their nominal detonation time. Furthermore, blast design parameters certainly affect vibration levels. Therefore, it is not possible to use a ground vibration record obtained from a production blast in finding a proper delay interval. Ground vibration records from signature blasts should be used to determine an optimum delay time. Since; F = 1/ T ⇒ T = 1/ F. In base of seismographs results, average of frequency is 34-44 (Hz) then,

T_V = 1/ 34.3 = 29.2 ms, T_L= 1/ 35.8 = 28 ms and T_T=1/ 44= 22.7 ms.

Delay time is the time of ½ a cycle or where the wave crosses zero. So the recommended delay time (Surface Delay Connector) will be half of the above calculated time, and is equal to 25 ms.(Table 7)

Table 7. recommendation for delay time

Avarege Frequence(HZ)	Transverse	Longitudinal	Vertical
	44.0	35.8	34.3
Surface Delay Connector (ms)	11.4	14.0	14.6

12. DISCUSSION AND CONCLUSIONS

A Part of the explosive energy is use to break the rock, and other part of it causes vibration. Ground vibration can have damage on nearby structures. In this project, drilling and blasting techniques usage for excavation of rock under the dam foundation. On the other hand, the grouting curtain was in the same area. The damage of blast shakes waves on the grouting curtain is significant. Therefore, it was necessary to determine the amount of charge per delay in each explosion to prevent the damage effect of explosion-induced vibration on the grouting curtain. Allowable vibration depending on the age of the grouting and its strength, it was determined. Then, with 15 experimental blasting and 30 seismic recordings by seismographs, the parameters K and β were determined by regression plotting. In each blasting, the amount of explosives and the distance of seismographs, Changed from drill hole. After determining the permissible vibration and the parameters $K = 325.36$ and $\beta = 1.1605$ which were dependent on the ground specification, based on the distance from the drill holes and the strength to grouting divided by age, the amount of charge per delay in each blasting was determined. By equitation (5), charge per delay can calculate the safe grouting at any distance from the blast site according to the grouting strengths. Small charges will generate vibrations with higher frequencies and smaller displacement. Large charges will generate vibrations with lower frequencies and larger displacement. If the area around the blasting site is rocky, with shallow soil cover, the vibration will be characterized by relatively higher frequencies and smaller displacement. If the area around the blasting site has a deep covering of soil (such as in an alluvial valley), the vibrations will be characterized by relatively lower frequencies and larger displacement. For specific conditions, it is recommended that if blasting is of critical importance with respect to a particular grouting project, and if the two activities cannot be sequenced such that grouting is conducted after blasting, the project may warrant a detailed on-site investigation and testing program to develop site-specific vibration criteria higher than those noted above. If such an investigation is conducted, it is recommended that vibrations be monitored both at the ground surface and below surface to the full depth of grouting.

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