Planning to Demonstrate Why High PPVs Work for Close-In Blasting

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Project Owners typically require General and Detailed Blast Plans when blasting close to important structures and specify the maximum allowable peak particle velocity for each potentially affected structure. Low, residential level PPV limits may be specified which significantly restricts the potential for blasting to be effectively used. Contractor's responding to these contract conditions typically cite historic case studies which may, or may not, apply to the specific situation and/or types of structures for which limits have been set. A long submittal cycle typically follows.

This paper examines approaches to developing General Blast Plans that respond to varying levels of allowable PPV; overviews pertinent historic data and case studies; details methods and procedures for estimating PPV, frequency, and stresses and strains in concrete structures; and presents test blasts designed to demonstrate compliance with limits. Case studies are presented where this blast planning process has been successfully applied with higher than typically allowable PPVs and a case where limits were not raised but blasting was successfully performed, albeit at a higher cost than if higher PPVs had been allowed. This blast planning process also focuses on demonstrating the acceptability of higher than commonly specified PPV limits.

The Authors hope that this paper will be of help to Owners preparing Controlled Blasting specifications and Blasting Contractors involved with close-in blasting work on small and large projects.

Introduction

This paper provides an overview of approaches to selecting blast vibration criteria for close-in blasting near concrete dams, spillway and intake structures, pipelines, water tanks and other steel and reinforced concrete structures encountered near blasting sites. It has been prepared to assist interested parties in further understanding the underlying issues, in particular, issues related to increasing the 2-in/sec peak particle velocity blasting criterion typically specified for blasting projects.

Project specifications typically indicate that the Contractor is expected to approach rock excavation in a conservative manner to minimize the potential for concrete and structure damage and to preserve the integrity of the rock mass in final cut slopes. Project blasting specifications typically establish:

1. A maximum, 2-in/sec (50 mm/sec) peak particle velocity for blast vibrations at permanent structures at frequencies greater than 40 Hz.
2. A requirement to further limit peak particle velocity for blast vibrations at "fresh concrete".
3. A requirement to preserve 75% of the "half barrels" or "hole traces" in final excavation walls.
4. A requirement to utilize mechanized and hand excavation methods to minimize vibration of the existing improvements and leave surfaces in the best practicable condition.

The paper is intended to be read by a broad spectrum of interested parties and to provide those readers with both a general and explicit understanding of the issues to be resolved, the risks involved, and the approach to quantifying potential impacts associated with blast vibrations.

Blast Effects and Blasting Criteria

According to Revey (2004), “where boreholes are filled with regular charges that fill or nearly fill the entire diameter of the drill hole, some crushing usually occurs in the rock around the charge. The extent of this compressive and shear failure zone is usually limited to one or two charge radii. Beyond the plastic crushing zone, the rock or ground is temporarily deformed by elastic strain waves. For some distance tangential strain intensity exceeds the rock’s tensile strength and new fractures are created. The magnitude of dynamic strain and particle motion decreases as distance from the charge increases. This process is called “attenuation”. When fully coupled charges (the explosive charge fills the hole completely) are used, radial cracks in rock can extend to a distance equal to 26 charge radii (Siskind and Frumanti, 1983).” Decoupled charges are typically used to prevent excessive radial cracking and vibration when blasting rock located at the excavation limits.

Blast Induced Vibration, PPV, Ground Displacements and Strain

At any given peak particle velocity (PPV) the amount of ground displacement is inversely proportional to frequency as represented in Equation 1.

$$Disp = \frac{PPV}{2.\pi.f} \quad \text{……………………………………………………(Equation 1)}$$

Where,
Disp = Displacement (inches, or millimeters)
PPV = Peak Particle Velocity (in/sec or mm/sec), and
f = Frequency (Hz)

The frequency of ground shaking is extremely high near the blast (>500 Hz) and attenuates to the natural frequency of the ground (10 to 30 Hz) (Revey, 2004) or nearby structures (1 to 6 Hz) with distance. Similarly, the PPV is high near the blast and attenuates with distance. This latter relationship is defined by the following equation:

$$PPV = K \times \left(\frac{D}{\sqrt{W}} \right)^{b} \quad \text{……………………………………………(Equation 2)}$$

Where,

PPV = Peak Particle Velocity (in/sec),
K = A constant between 40 and 240, a value of 240 is used in the examples below.
b = a constant between –1.2 and –1.6, a value of –1.6 is used in the examples below.
D = Distance from the blast (ft)
W = Maximum weight of explosives per 8ms delay
The ratio $D/\sqrt{W}$ is also known as the “scaled distance”.

Revey (2004) provides the following example…”the frequency of motion and PPV generated by a one-pound (0.45 kg) decoupled detonating cord charge located five-feet from a structure would respectively be around 500 Hz and 15 in/sec (380 mm/sec). The temporary elastic particle displacement caused by the very high frequency motion would be around 0.005 inches (0.13 mm) {[PPV/(2 x pi x *f*)] or [(15/(2 x 3.14 x 500)]}. In comparison, the temporary elastic particle displacement associated with a blast generating a regulatory compliant PPV of 2 in/sec (50 mm/sec) at frequency of 20 to 30 Hz is three times higher at 0.015 inches (0.38 mm).” Neither of these temporary elastic displacements would be expected to cause damage in steel pipelines or reinforced concrete structures.

Approach to Selecting "Safe" Vibration Criteria

A large majority of projects maintain conservative blast vibration criteria (e.g., 2-in/sec (50 mm/sec) at 40 Hz or higher frequency) because it is un-necessary to utilize higher limits typically because blasting is carried out remote from important structures. However, lower limits may also be selected when the potential consequences of blast vibration damage are unacceptable and/or an accurate prediction of actual blasting impacts is conditioned by unacceptable uncertainty.

In general, the case for higher allowable blast vibration criteria is typically made using empirical data and experience with or without supporting theoretical analysis.

Empirical Data and Experience

TVA Blast Vibration Criteria

Oriard 1980 is frequently referenced as an early source of blast vibration criteria for large concrete structures. Table 1 contains the cited criteria from Table 3 in Oriard's paper.

Table 1: TVA Blast Damage Criteria for Mass Concrete

Concrete Age from Batching	Allowable Particle Velocities from Blast Induced Vibrations (in/sec)
0	4 (in/sec) or 100 (mm/sec) x DF
4-hrs to 1-day	6 (in/sec) or 150 (mm/sec) x DF
1 –to- 3 days	9 (in/sec) or 225 (mm/sec) x DF
3 –to- 7 days	12 (in/sec) or 300 (mm/sec) x DF
7 –to- 10 days	15 (in/sec) or 375 (mm/sec) x DF
10 days or more	20 (in/sec) or 500 (mm/sec) x DF

DF is a "Distance Factor" designed to incorporate frequency considerations into the damage prediction model. "DF" varies with distance as shown in Table 2.

Table 2: Distance Factor "DF"

Distance Factor "DF"	Distance from Blast to Concrete Structure (ft)
1	0 –to- 50
0.8	50 –to- 150
0.7	150 –to- 250
0.6	> 250

Blast damage criteria developed by TVA were for mass concrete with mass concrete defined as:

> "……….reinforced or un-reinforced concrete resting on a rock foundation and having a vertical projection less than twice the minimum horizontal dimension."

Dam No. 3 in Minneapolis (Tart et al, 1980)

This project involved removal of concrete from the lock walls to improve the hydraulics of filling and emptying conduits located in the lock walls. Small blasts were detonated and monitored using dynamic strain gages, accelerometers, and geophones (in the far-field). Table 3 has been reproduced from this report.

Table 3: Five Levels of Theoretical and Observed Blast Damage Effects

Effects	Strain (x 10^{-6})	Particle Velocity in/sec (mm/sec)
Theoretical static failure in tension	140	20 (500)
Spalling of freshly set grout	700	100 (2,500)
Spalling of loose or weathered surface skin	1,300	200 (5,000)
Cracks develop extending from shot holes	2,400	375 (9,375)
Mass concrete blown out	3,800	600 (15,000)

The paper concluded that it was possible to develop strain criteria for damage and that strains were predictable.

US Bureau of Reclamation Criteria

US Bureau of Reclamation criteria for blasting near concrete structures, including dams, allow a limit of 4 in/sec (100 mm/sec). Blasts, conforming to this criterion, have been detonated a few tens of feet away from existing concrete structures at the Tieton Dam in Eastern Washington.

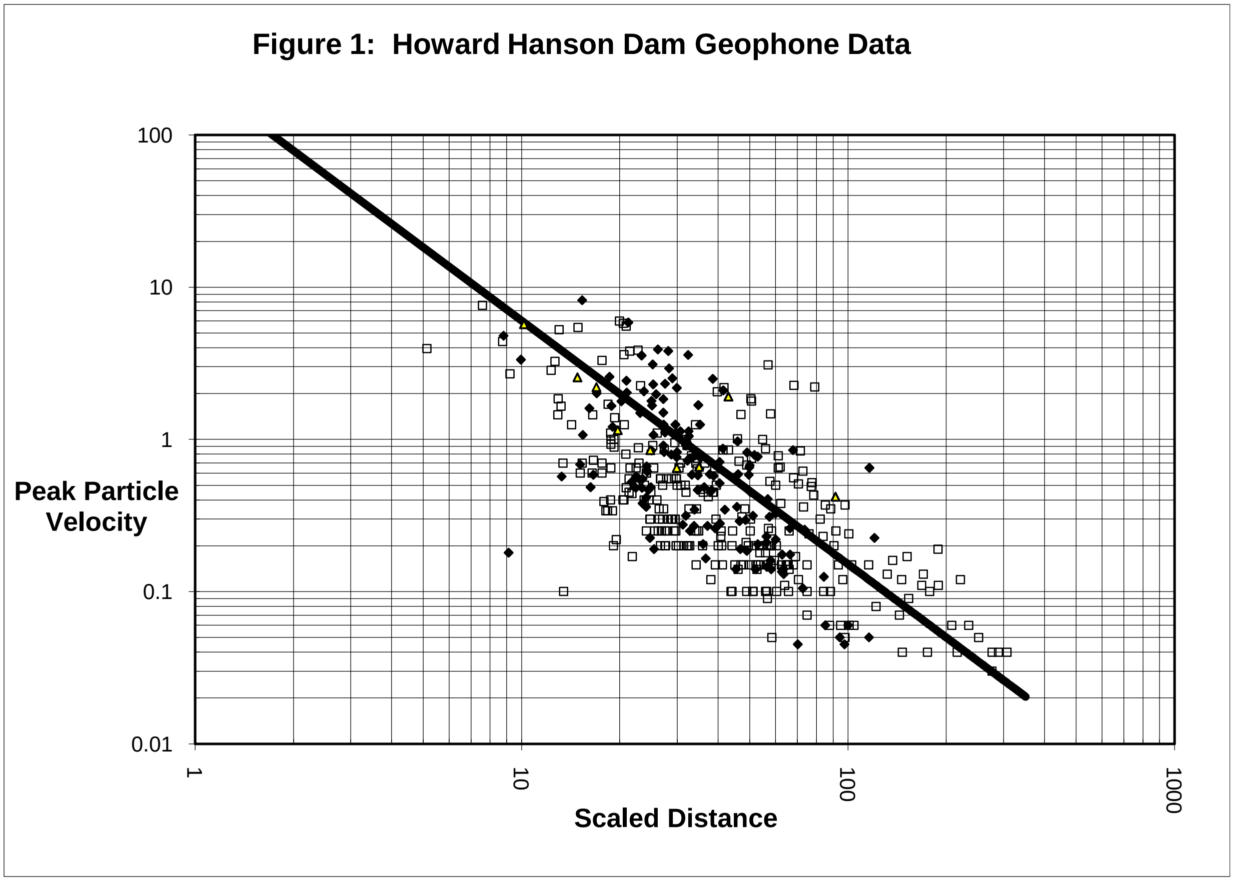
USACE at the Howard Hanson Dam

A recent USACE project at the Howard Hanson Dam in Washington State (SubTerra, Inc., 2007) has allowed vibration levels of up to 6-in/sec (150 mm/sec) at gate operating equipment and 16 in/sec (400 mm/sec) at existing concrete intake tower and dam structures. In this case, blasts were detonated to remove rock from against the existing concrete structures that were built in the mid 1960’s. Approximately 70 blasts were detonated at this project with each blast monitored at ten or more locations on the ground surface and on and within the concrete structures. The summarized data set are provided in Figure 1.

It is of note that none of the blasts resulted in peak particle velocities greater than 10-in/sec (250 mm/sec) even though the specification allowed up to 16-in/sec (400 mm/sec) and most blasts were designed with scaled distances of less than 10. It is also of note that Oriard’s suggested $k = 242$ and $b = -1.6$ (see Equation 2), as plotted in Figure 1, represents the average magnitude(s) of vibrations that were measured.

Vibration Effects in Taller Structures

One of the limitations associated with direct application of the previously noted TVA criteria is the limitation implied in Oriard, 1980 that the criteria apply to concrete structures that have height:width ratios of less than 2. Several recently completed projects have indicated that amplification can occur in structures that are several times taller than they are wide.



Trench Blasting Near Pipelines and Utilities

There is a considerable body of experience documented in the library maintained by the International Society of Explosives Engineers (ISEE) regarding blasting effects on buried pipelines and utilities. The following paragraphs summarize some of this experience.

Pressurized Steel Pipelines: Siskind et al in RI 9523 (Siskind et al, 1995) report on surface mine blast effects on pressurized steel and PVC pipelines concluding that ..” *it is recommended that 5 in/sec (125 mm/s)* ***measured at the surface*** *is a safe-level criterion for large surface mine blasts for Grade B or better steel pipelines. The same criterion is recommended for SDR 26 or better PVC pipe”* This study also found that PPV at a depth of about 3-ft were 40% less than PPV measured at the surface.

Aimone-Martin and Clah (2003) describe similar results for coal mine blasting near 30-in diameter, high pressure (845 psi (5.8 MPa)) gas pipelines that were subject to vibrations measured at the surface above the pipe up to 6 in/sec (150 mm/sec) at 17 Hz. They concluded that all blasting near the pipeline was well below the limits that could cause damage to the pipeline.

Oriard (1994) describes a project where blasts were to be conducted within 14-ft (4.3 m) of a buried pipeline. A test “mockup” section of the pipe was installed and subject to blasts that produced up to 63 in/sec (1,575 mm/sec) at the pipe without damage to the pipe.

Separately, Williams Gas Pipelines, a major operator of cross country gas pipelines allows, in their operating procedures, peak particle velocities up to 5 in/sec (125 mm/sec).

These and numerous other references firmly support the conclusion that peak particle velocities up to 5-in/sec (125 mm/sec) should not cause damage to pressurized pipelines.

Concrete Encased Utilities and Duct Banks: Anderson et al (2004) describe a project where trench blasting was carried out inside the Weehawken tunnel to create space in the invert of the tunnel for relocating two 230 KV oilostatic (pressurized oil conduit) duct banks. The duct banks ran on the floor at the base of each tunnel wall and were within 3-ft (1 m) of the blasting that took place. Blasting was successfully carried out subjecting each duct bank to 500 microstrain without damage.

There are several conclusions that can be developed from these collective experiences:

- Peak particle velocities up to 5-in/sec (250 mm/sec) do not cause damage to pressurized pipelines, even when vibrations occur at relatively low frequency (i.e., < 20 Hz).
- Blasting has been carried out within 3-ft (1 m) of concrete encased utilities and duct banks subjecting those structures to strains up to 500 microstrain without causing damage.

Theoretical Considerations

As Oriard notes in his 1980 paper, "The observed ability of concrete to resist vibration damage is difficult to justify theoretically"; this observation remains true some 30-years following Oriard's publication. Typically, calculated dynamic strains, and/or stresses, are predicted to be several times higher than required to cause damage in concrete based on static strain or strength considerations.

Predictions Based on Sonic Velocity

Oriard, 1980 and Dowding, 1985 are two of several refererences that develop a relationship between propagation velocity and dynamic stress. The prediction equation is written as follows:

$$\sigma = \left(\frac{rc}{12^3}\right) * \left(\frac{1}{32}\right) * PPV \text{ ……………………………………….(Equation 3)}$$

where,

σ = Dynamic stress (psi)
r = Mass density (lb/ft^3)
c = concrete sonic velocity (ft/sec)
PPV = Peak Particle Velocity (in/sec)

As noted by Oriard (1980), a dynamic stress of 2,225 psi (15.3 MPa) would be calculated for a peak particle velocity of 100-in/sec (2,500 mm/sec) with c = 8,300 and r = 150. A dynamic stress of 225 psi (1.6 MPa) is calculated for PPV = 10 in/sec (250 mm/sec).

Recent publications have indicated dynamic compressive strength to be 1.5 times static and dynamic tensile strength to be up to five (5) times static. This provides one explanation for the apparent inability of theoretical analyses to validate field observations regarding the lack of near field blast damage.

Single Degree of Freedom Model (after Dowding, 1985)

Dowding has developed three equations to predict peak particle displacement (PPD), peak particle velocity (PPV), and peak particle acceleration (PPA):

$$PPD = 0.0028\left(\frac{100}{R}\right)^{1.1}\left(\frac{10{,}000}{c}\right)^{1.4}\left(\frac{W}{10}\right)^{0.7}\left(\frac{4.66}{\rho}\right)^{0.7} \text{…………(Equation 4)}$$

where,
PPD = Peak Displacement (inches)
R = Distance from blast to point of prediction (ft).
c = compressive wave propagation velocity (ft/sec)
W = Maximum weight of explosives per 8ms delay (lbs).
ρ = Density, usually ignored.

$$PPV = 0.72\left(\frac{100}{R}\right)^{1.46}\left(\frac{W}{10}\right)^{0.48}\left(\frac{4.66}{\rho}\right)^{0.48} \text{………………………(Equation 5)}$$

where,

PPV = Peak Particle Velocity (in/sec).

$$PPA = 314\left(\frac{100}{R}\right)^{1.84}\left(\frac{c}{10{,}000}\right)^{1.45}\left(\frac{W}{10}\right)^{0.28}\left(\frac{4.66}{\rho}\right)^{0.28} \text{…………...(Equation 6)}$$

where,

PPA = Peak Particle Acceleration (in/sec^2)

Predicted values are then used to estimate a range in frequency response using tripartite paper. Stresses can be calculated from differential displacements (converted to strains) using the elastic modulus for the potentially impacted material. Metric versions of these equations are available in the references listed at the end of the paper.

General "Controlled" Blast Planning

General Blasting Plans are typically prepared by the Blasting Contractor to communicate planned blasting practices and demonstrate conformance with the project's specifications. The GBP will define the controlled blasting methods proposed for use, evaluate blasting risks, explain planned controls and monitoring procedures, and describe specific controlled blasting methods.

Blast management methods that will be applied to ensure positive communications and coordination with the required stakeholders are typically laid out.

Controlled Blasting Objectives

Blasting in this example project includes excavation of the abutments and foundation areas immediately below a dam and blasting adjacent to a hydroelectric powerhouse containing 20 MW generators. Blasting work needed to be designed and executed to meet the following main objectives:

1. Flyrock must be controlled to protect the public, workers and structures.
2. Charges must be designed to control vibration that could negatively affect the operation of the adjacent facilities.
3. Blast-induced ground vibrations must not exceed those levels that could cause structural damage.
4. Blast design and execution must minimize the potential for misfires, premature detonations, dead-pressing of explosives charges and sympathetic detonations.

5. Blasts must be designed and executed in a timely and efficient manner so that the critical work can be accomplished in a timely fashion.

The following paragraphs provide estimates of blasting performance for various hole layouts, explosives decking, and variations in maximum charge weight. A program of Test Blasting is subsequently described that demonstrates blast performance prior to application in the near field environment.

Approach to Blast Design

The blast designs evaluated below have the following common characteristics:

- Bench height = 20-ft
- Drilled Depth = bench height plus 2-ft (subdrill)
- Decking as required to minimize charge weight per 8 ms delay.

The number of rows would depend on the initiation system with limitations on available millisecond delays and the potential for charge interaction when a long duration round is employed. Recent developments in electronic blasting eliminate most concerns with a modest increase in overall blasting materials costs and improvements in fragmentation.

Round within 10-ft (3.05 m)

A typical near-field round located 10-ft (3.05 m) from the reinforced concrete structures might include a 1.5-ft (0.46 m) spacing on trim holes, a 2-ft (0.61 m) burden to buffer holes and a 3-ft (0.91 m) by 3-ft (0.91 m) hole pattern in the main round. The maximum weight per delay would be 4.4-lb (2 kg) assuming a loading density of 1-lb/CY (0.59 kg/m^3) for buffer and 1.2-lb/CY (0.71 kg/m^3) in the main round and explosives distributed in 2-decks. The following performance characteristics have been estimated by application of the formulae described above:

Scaled Distance: 6.7
Peak Particle Velocity (Oriard): 11.5 in/s (292 mm/s)
Estimated Displacement: 0.0159 in (0.40 mm)
Estimated Strain: 100×10^{-6}
Estimated Concrete Stress (Sonic): 280 psi (1.9 MPa)
Estimated Concrete Stress (E x e): 540 psi (3.7 MPa)

Round within 20-ft (6.1 m)

A typical near-field round located 20-ft (6.1 m) from the reinforced concrete structures might include a 1.5-ft (0.46 m) spacing on trim holes, a 2-ft (0.61 m) burden to buffer holes and a 5-ft (1.52 m) by 6-ft (1.83 m) hole pattern in the main round. The maximum weight per delay would be 14.6-lbs (6.62 kg) (main round) assuming a loading density of 1-lb/CY (0.59 kg/m^3) for buffer and 1.2 lb/CY (0.71 kg/m^3) in the main round and two decks per hole. The following performance characteristics have been estimated by application of the formulae described above:

Scaled Distance: 6.3
Peak Particle Velocity (Oriard): 12.7 in/s (323 mm/s)
Estimated Displacement: 0.0204 in (0.52 mm)
Estimated Strain: 100×10^{-6}
Estimated Concrete Stress (Sonic): 310 psi (2.1 MPa)
Estimated Concrete Stress (E x e): 330 psi (2.3 MPa)

Round within 40-ft (12.2 m)

A typical bench round might include a 6-ft (1.83 m) by 6-ft (1.83 m) pattern of 3-in (75 mm) diameter blastholes. The maximum weight per hole would be 35.2-lbs (16 kg) assuming a loading density of 1.2 lb/CY (0.71 kg/m^3). The following performance characteristics have been estimated by application of the formulae described above:

	Single Deck		Two Decks	
Scaled Distance:	7.4		10.5	
Peak Particle Velocity (Oriard):	9.7 in/s	(246 mm/s)	5.6 in/s	(142 mm/s)
Estimated Displacement:	0.0193 in	(0.49 mm)	0.0119 in	(0.30 mm)
Estimated Strain:	40 x 10^{-6}		20 x 10^{-6}	
Estimated Concrete Stress (Sonic):	230 psi	(1.6 MPa)	130 psi	(0.9 MPa)
Estimated Concrete Stress (E x e):	200 psi	(1.4 MPa)	120 psi	(0.8 MPa)

Trim Blasting

Holes along the cut line or final slope would be drilled at close spacing (say 1.5 (0.46 m) to 3-ft (0.91 m)) and loaded with lighter, decoupled charges (e.g., 7/8-in (22 mm) diameter powder laced with 50 grain detonating chord) designed to provide a loading density of from 0.07 to 0.09 pounds per square foot (0.34 to 0.44 kg/m^2). These trim holes would be fired in sequence with the main round after the holes immediately in front of each trim hole had been detonated. The following performance characteristics were estimated for a 20-ft double decked line with holes on 1.5-ft centers located a distance of 10-ft from a structure.

Scaled Distance:	9.8	
Peak Particle Velocity (Oriard):	6.3 in/s	(160 mm/s)
Estimated Displacement:	0.0084 in	(0.21 mm)
Estimated Strain:	80 x 10^{-6}	
Estimated Concrete Stress (Sonic):	150 psi	(1 MPa)
Estimated Concrete Stress (E x e):	400 psi	(2.8 MPa)

This analysis does not account for the effects of decoupling (i.e., explosives decoupled from the sides of the blasthole) that will reduce the calculated impacts.

Test Blast Design and Instrumentation

Where possible, the test blasting program would begin in an area further away from the structures of interest and use simple mock-ups of the actual structures to demonstrate blast performance. The “mock-up” should be as simple as possible to avoid the need for complex analyses.

Blast Monitoring Instrumentation

Tart and Oriard’s paper notes that, ”it is inappropriate to use conventional blast monitoring instrumentation to measure close-in vibrations from small charges”. They go on to note that, ”the frequency response of such instruments is too limited to permit registering the true vibrations”. It is the authors experience that close-in monitoring commonly requires the use of high frequency geophones and/or accelerometers.

Geophones should be positioned on the structure and on the ground near the structure; ten or more seismographs are typically deployed during test blasting to maximize the data available from each blast. Monitoring vibrations at key locations on the potentially affected structures along with deflections and/or strains is recommended as the blasting progresses. Several different types of geotechnical instrumentation are available to monitor "static" effects with a limited number of specialty instruments designed to monitor dynamic effects.

Blast Video

We strongly recommend that each blast be recorded using digital video. This video could then be reviewed by the Owner, Regulator, BIC and Blasting Consultant(s) after each blast and should become part of the Project's Blast Records. Conventional, nominal 30 frames per second (fps) systems typically provide adequate data with high speed digital cameras capable of several thousand fps available for specialty work.

Geotechnical Instrumentation

Concerns may be raised regarding the potential for blasting to increase the potential for slope instability especially if increases to the maximum permitted bench height are required to improve blasting efficiency. There are several instrumentation schemes that could be applied to monitor potential impacts.

Precise Surveying of Survey Prisms: Accurate face displacements can be measured using precise survey techniques and survey prisms glued or bolted to the rock or concrete faces that need to be monitored.

Inclinometer: Permanent inclinometer installations would be located at strategic locations and measured prior to and following each blast. The resulting slope movements would be reviewed against the blasting records and changes made to the following blast design as appropriate. An inclinometer installation typically involves installation of a 2.75-in inside diameter slotted, inclinometer casing.

Multipoint Borehole Extensometers: Multi-point Borehole extensometers using either stainless steel or, more commonly, fiberglass rods are typically installed in 3-inch diameter boreholes that can be drilled using the blasthole drilling equipment. Installations in up to 150-ft deep or longer boreholes are feasible; boreholes may be either vertical or horizontal.

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