Criteria for Controlled Close Proximity Blasting at the Oroville Dam Spillways and Flood Control Structure

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Abstract-- Emergency work to restore the Oroville Dam spillways required excavation of hard rock and concrete near critical structures, including the Radial Gate Structure and the Emergency Spillway Monolith Structure. Because of the large volume of demolition involved, and the emergency pace of construction required, mechanical excavation methods were deemed impractical for this project. It was also realized that traditional blasting criteria for close-in blasting would lead to unacceptable schedule delays. These challenges led the designers, consultants, and regulators toward innovative changes in the blasting specifications, based on principles presented in this paper. Case history data characterizing the behavior of high frequency blast vibrations and resulting transient strain in mass concrete structures is limited. Historically, regulatory criteria have been focused primarily on Peak Particle Velocity (PPV) developed decades ago to prevent the creation of cosmetic hairline cracks in one and two-story wood-frame homes with gypsum and plaster walls; materials very dissimilar from reinforced concrete structures. This paper presents monitoring results for close-in controlled blasts performed at the Oroville Dam main spillway. Results from this study illustrated that (a) measured values of PPV up to 55 inches/second (ips) at high dominant frequencies (300 to 1250 Hz) resulted in no visual signs of damage to the concrete slab, (b) peak strain decreased exponentially with distance away from the blast sites with negligible strain beyond a distance of 100 feet, and (c) the relationship between peak strain and PPV shows promise but additional data is needed to improve its characterization, particularly at strain levels greater than 100 microstrain. Monitoring peak strain provides a direct way to calculate stresses and to compare to a single allowable stress parameter.

I. Introduction

The Oroville Dam, located east of Oroville, California, on the Feather River, is a 770-foot high earth embankment dam constructed between 1961 and 1968. The dam has two spillways including the main spillway structure, referred to as Flood Control Outlet (FCO), and an Emergency Spillway consisting of monoliths and ogee weirs intended to pass extreme flows above the FCO capacity of approximately 300,000 cfs. The main spillway is a rectangular chute about 180 feet wide and about 3050 feet long with approximately 20 to 34-foot-high walls. Figure 1 shows the FCO gate structure and upper chute. The thickness of the chute invert slab was varied from about 1.5 to 4 feet, with #5 bars on 12-inch centers, both directions. Lateral drains were installed beneath the invert without additional excavation, which reduced the slab thickness to just seven inches over the drain lines.

A section of the concrete spillway chute uplifted during moderate spillway flows, which exposed the foundation to erosion during subsequent spillway use that was required to pass incoming storms. Eventually, soil and rock were eroded into the channel from beneath and around the spillway chute. Groups of engineers and specialists were quickly mobilized to plan repairs and design improved primary and emergency spillways. With an expedited selection process, a Contractor was retained to: 1) clean out and place about 350,000 cubic yards of concrete in huge holes in scoured ground and, 2) rebuild spillway structures as designs evolved during the work. All this activity, with up to 500 workers on site, is anticipated to be completed by November 2018, approximately 21 months after the damage occurred.

Many forms of blasting were needed to accomplish this work. First, rock was drilled and blasted to establish safe access for work needed to clean and fill the 150-foot deep scour hole with Roller Compacted Concrete (RCC). Quarry blasting was performed to provide aggregate for RCC and structural concrete placements on the site. The most challenging blasting was part of the concrete demolition work that occurred very close to concrete structures that would remain in service.

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Figure 1. Main Spillway Slab and Gate Structure.

II. BACKGROUND

It is common to see specifications for infrastructure projects involving concrete and steel structures to include vibration criteria in the 2 inches/second (ips) range or lower. Several studies dating back to the 1940's examined vibration records together with observed damage to residential structures and concluded that limiting peak particle velocity to 2 ips or less would reduce most problems associated with cracks in dry wall or plaster. A 2 ips criteria is reasonable for typical wood-framed residential structures near uncontrolled production blasting such as a quarry. Unfortunately, these limits are often applied to other structures regardless of additional controls, location, or type of structure. Because this conservative approach worked, there was little incentive to improve the state of practice, and a lack of high-quality research to support changes to the practice. A summary of three relevant studies follows.

Nicholls et al, 1971 [2] presented a summary analysis of blast monitoring results obtained from three published studies on vibration and damage and provided recommendations for threshold criteria for residential structures. Three levels of damage were classified as "no damage", "minor damage" and "major damage" where "minor damage" is characterized by the development of fine cracks or the opening of existing cracks in plaster or dry wall and "major damage" includes the development of cracks in plaster or dry wall. The results of this study indicate minor and major damage threshold levels at 5.4 and 7.6 ips, respectively. The report also pointed out that PPV values used for the study were derived from displacement or acceleration readings converted to velocity using simple harmonic motion calculations. This implies that the reported threshold levels of 5.4 and 7.6 ips are likely greater. Nicholls et al, 1971 [2] ultimately recommended a safe vibration criterion for residential structures of 2 ips for any directional component.

A study by Siskind et al, 1980 [4] presented in USBM Report of Investigation 8507 (RI8507) has greatly influenced vibration limits adopted by US government agencies; and limits applied in specifications for civil construction projects. The USBM report included ten published studies with 553 observation cases relating to blasting vibrations and observed damage to residential structures. The referenced report suggested safe vibration levels of 0.5 ips for signals with dominant frequencies below 40 Hz and 2.0 ips above 40 Hz. The report also suggested the need to perform spectral analysis in order to apply these vibration criteria appropriately. Throughout the Report, the authors clearly indicate the criteria were intended solely for residential structures. Moreover, these limits are set to provide 95% confidence of preventing cosmetic cracks in plaster or sheetrock walls.

There are some cases where Engineers and Facility Owner/Operators have understood that concrete structures can withstand much higher levels of vibration than limits commonly applied to protect drywall. In one such case, a test blasting program by Tart, Oriard and Plump (1980) [5] was designed to evaluate the feasibility of using very light charges configured from detonating cord to enlarge and modify water flow conduits at Lock and Dam No. 1 on the Mississippi River. For this work, the challenge was to develop charges for holes drilled parallel to the existing conduit that would sequentially break concrete into the opening without damaging the remaining concrete wall. The general configuration of the extremely careful blasting that was ultimately applied to expand the conduits is shown in Figure 2.

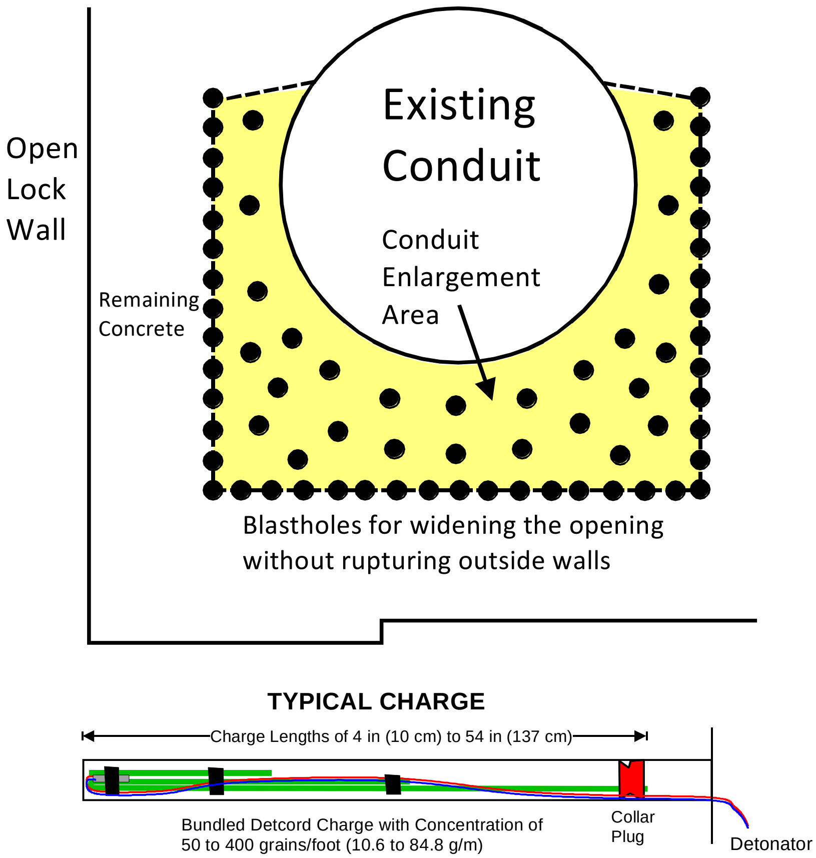

Figure 2. Typical configuration of blastholes and charges used to Enlarge Conduits at Lock and Dam No. 1.

Strain gauges and piezo-resistive accelerometers were placed as close as 8 inches to 32 inches from the explosive charges. The authors observed and reported four types of impacts occurring in concrete in the intended conduit widening area. They were 1) grout spall, 2) concrete skin spall, 3) cracking, and 4) blowout. The levels of strain and comparable PPV of these impacts reported by the authors are shown in Table 1.

Table 1. Strain and Comparable PPV for Various Failure Modes of Concrete at Lock and Dam No. 1

Level of Effect	Strain (microinches/inch)	Particle Velocity (in/s)
Grout spall	700	100
Skin Spall	1300	200
Cracking	2400	375
Blowout	3800	600

It is important to note that all of the cracking, spalling and blowout breakage occurred within the intended excavation area. Despite very high PPV levels, exceeding 1,000 in/s, the two or so feet of concrete between the enlarged conduit and open lock walls was not damaged. The use of light charges to successively chisel away about 8 inches of concrete per hole was the key to the success of this work. This study and successful application of carefully controlled blasting with light charges and adequate relief towards the intended breakage zone demonstrates that successful blasting work can be done despite high levels of vibration.

Regulatory Requirements

Blasting regulations for dams, and their appurtenant structures, should be conservative with an appropriate factor of safety or risk-based criteria. Changing regulations can be controversial, especially when the regulations have a long history of successful practice and the change appears to be reducing the margin of safety. There must be a compelling need to change, the changes must be supported by good science, and the new regulations must provide an appropriate margin of safety. There is a compelling need to change the 2 ips "standard" PPV criterion for close-in blasting conditions. There is good science to support changing this regulation, and an appropriate margin of safety can be provided with proper attention to details based on engineering principles. The proposed changes in criteria must be combined with associated changes in methods for close-in blasting. Relaxing the commonly used criterion of 2 ips must also include additional measures to ensure light charges are used and proper decoupling is provided to prevent direct rupture damage. In addition, more parameters such as strain and vibration frequency must be monitored. A comprehensive approach, based on good science, and monitored with modern technology can reassure the regulator that the margin of safety is appropriate and the risk can be managed successfully. To properly implement these changes in blasting regulations, it is also imperative to have an experienced blasting contractor with diligent oversight by a knowledgeable team providing consistent quality control and quality assurance. With all of these conditions in place, close-in blasting of critical structures can be successfully performed in a more cost-effective manner than currently allowed by traditional regulations, while maintaining an appropriate margin of safety.

A. Blast Vibration Limits at Oroville Dam

From the outset, it was understood that concurrent blasting and concrete placement work would be necessary to accelerate the completion of this work. If traditional peak particle velocity limits typically ranging from 2.0 to 4.0 ips were applied, another year or two of time would have been needed to complete the demolition and the increased cost would have exceeded hundreds of millions of dollars. More importantly, exposing the population of Oroville to damaged spillways for more seasons of winter water release was not an acceptable option.

As expected, there was elevated concern about vibration impacts on existing concrete structures and new concrete being placed near blast areas. In some cases, leveling concrete in the new spillway had cured less than a day when shallow rock grading blasts occurred within ten feet of the concrete. To accommodate the concurrent work, initial blasting specifications at Oroville Dam included PPV limits for concrete based on age. Limits ranged from 2.0 to 10.0 ips for concrete aged from 4 hours to 10 days or older. Distance-related reduction factors were applied to lower the PPV limits for more distant blasts to account for lower expected frequencies of motion. These PPV limits were based on criteria developed by Oriard and Coulson (1980) [3]. Since some of the concrete structures at Oroville Dam, like the FCO structure would have higher height to width ratios than the spillway slab; and due to elevated concern, the PPV limits, ranging from 4 to 20 ips in the published Oriard criteria [3], were cut in half for this work. These limits were applied without incident for the Year 2017 construction season during which rock demolition blasting was occurring over 1,000 feet from the critical FCO structure.

Concerns were heightened for the 2018 season during which blasting would occur within 25 feet of the FCO structure and within 10 feet of the Ogee Weir of the Emergency Spillway. To prepare for this work, the close-in blasting study presented in this paper was conducted on a concrete section of the main spillway in Year 2017.

B. Test Blast Charge Configurations

Two separate tests blasts were designed for this study. In Test Blast 1, as shown in Figure 3, decoupled charges were used in the closest holes to minimize the potential for damage past a cold joint located 1.5 feet from closest holes. One and a half-inch and 7/8-inch diameter charges were used in respective buffer and trim holes. Two-inch diameter emulsion charges were used in the remaining holes in Blast 1 and in all the holes used in Blast 2. Charge-per-delay in Blast 1, initiated with electronic detonators was 6.0 pounds per delay. Conventional shock-tube detonators were used in Blast 2 with a charge-per-delay of 12 pounds.

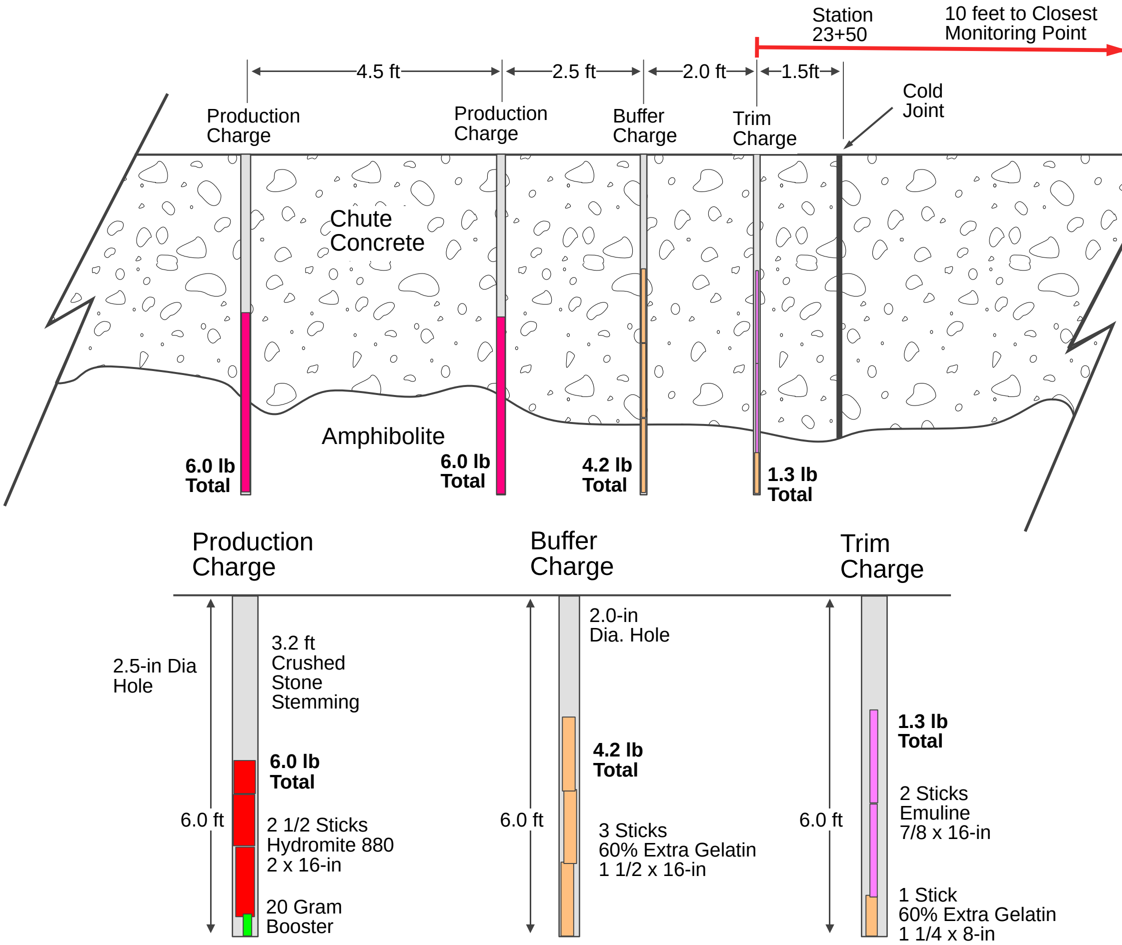

Figure 3. Test Blast Charge Configurations.

C. Strain Monitoring with Allowable Stress Based Limits

Vibration criteria is well established for limiting damage to residential structures, but there is a general lack of rational PPV based vibration criteria for reinforced concrete structures. Oriard and Coulson (1980) developed PPV limits for mass concrete with distance factors that reduced recommended PPV to account for lower frequencies of motion with increasing distance [3]. Acceleration measurements, sonic velocity testing, and lab strength measurements of vibration-impacted concrete and control cylinders were performed to evaluate blast effects [3]. No direct dynamic strain measurements were performed in the Oriard and Coulson study [3]. It is well known that the strength of concrete structures is greater under dynamic loading conditions compared to static loading, and the performance of concrete increases with increasing loading rate. Close-in blasting results in a dynamic loading condition with rapid loading rates and high frequencies of motion. Controlling damage to concrete piles is regularly accomplished by monitoring dynamic stresses during pile driving. The loading conditions for pile driving are analogous to blasting events adjacent to concrete structures. For conventionally reinforced concrete piles, the Federal Highway Administration (Publication No. FHWA NHI-05-042) recommends limiting compressive stresses to 0.85*f'c (concrete compressive strength) and tension stresses to 0.7*fy (steel yield strength) [1]. Similar to the established practice of monitoring pile driving, measuring strain represents a rational way to obtain dynamic stresses in concrete structures subject to nearby blasting. Laboratory test results on core samples obtained from the spillway slab indicate average compressive strength of 6,050 psi and modulus of elasticity of 4,100 ksi. Allowable tension and compression strain limits of 870 and 1,060 microstrain, respectively, can be calculated using the previously mentioned FHWA formulas together with the concrete test results and a steel yield strength of 36 ksi and modulus of 29,000 ksi. These strain levels are based on criteria for allowable pile driving stresses per the FHWA NHI-05-042 publication and provide an alternative viewpoint to the PPV-based limits.

III. INSTRUMENTATION AND MONITORING PROGRAM

Vibrations produced by blasting are typically monitored using conventional compliance equipment, such as seismographs with geophone sensors, designed to capture peak particle velocity and dominant frequency from recorded signals. The purpose of the subject instrumentation program was to measure blast induced motion and strain in the concrete spillway and characterize the relationships between PPV, acceleration and strain with distance from the blast areas. Because strains were measured, direct evaluations were made regarding PPV and possible impacts to concrete and other heavy civil structures in the vicinity of the blast area.

A. Instrumentation

Accelerometers and strain gages were installed on the main spillway slab at 9 stations located at different distances from the blast areas as shown on Figure 4. A total of 19 accelerometers and 12 strain gage sensors were mounted to the surface of the chute invert slab and FCO wall. Sensors were mounted to the chute invert slab and FCO wall with the following orientations: (a) longitudinal direction parallel to the spillway chute slab and parallel to the FCO walls, (b) transverse direction parallel to spillway chute slab and perpendicular to the FCO walls, and (c) vertical direction perpendicular to the spillway chute slab.

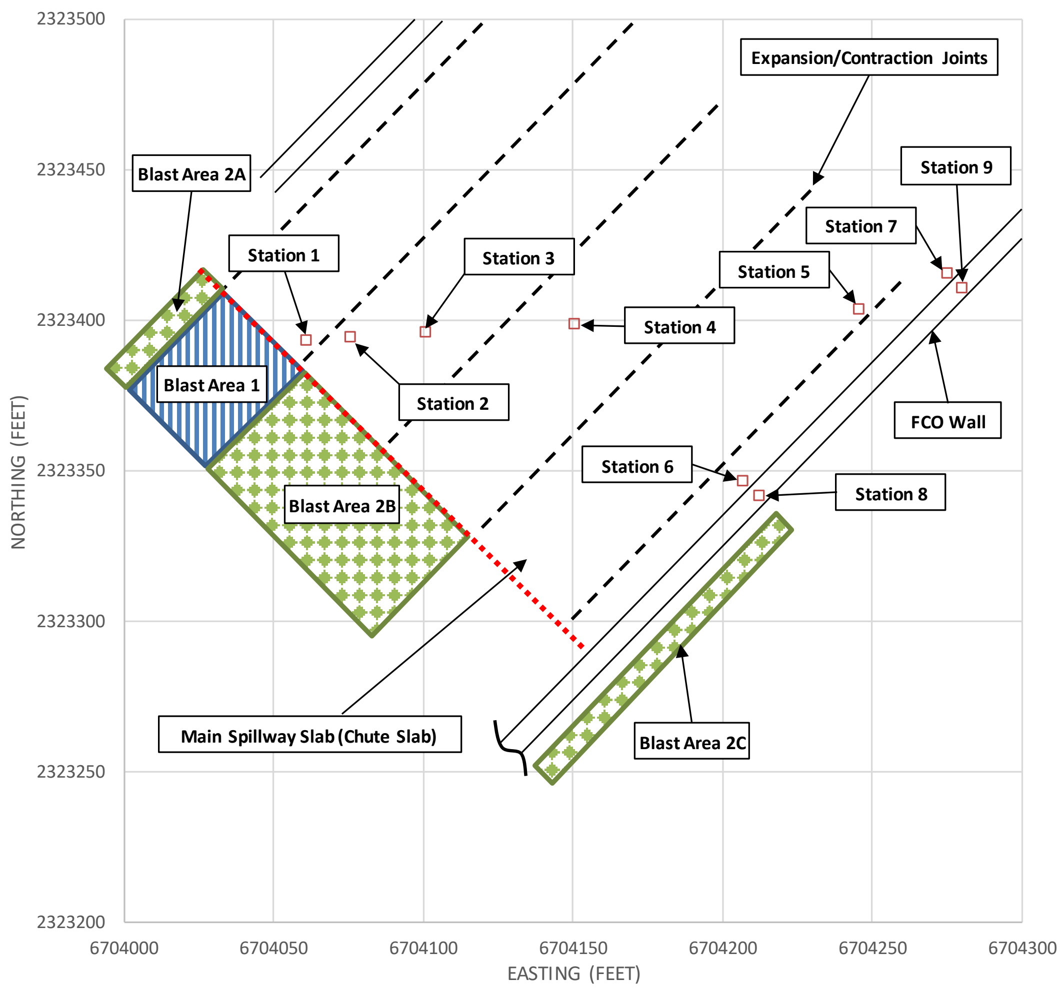

Figure 4. Plan View of Blast Instrumentation Layout on Main Spillway Slab.

IV. BLAST MONITORING RESULTS

Vibrations from two blast events were monitored on June 30, 2017 using instruments installed on the main spillway slab. Velocity time histories were calculated by integrating acceleration records, and PPV values were calculated from the velocity results for each measurement direction. A relationship between the resultant PPV and scaled distance for the main chute slab is shown in Figure 5. The frequency content of each acceleration, strain and computed velocity record was characterized by applying a fast Fourier transform (FFT) to the time history data. Results from FFT plots indicate dominant acceleration frequencies ranging from about 300 to 1,250 Hz for the main spillway blasts.

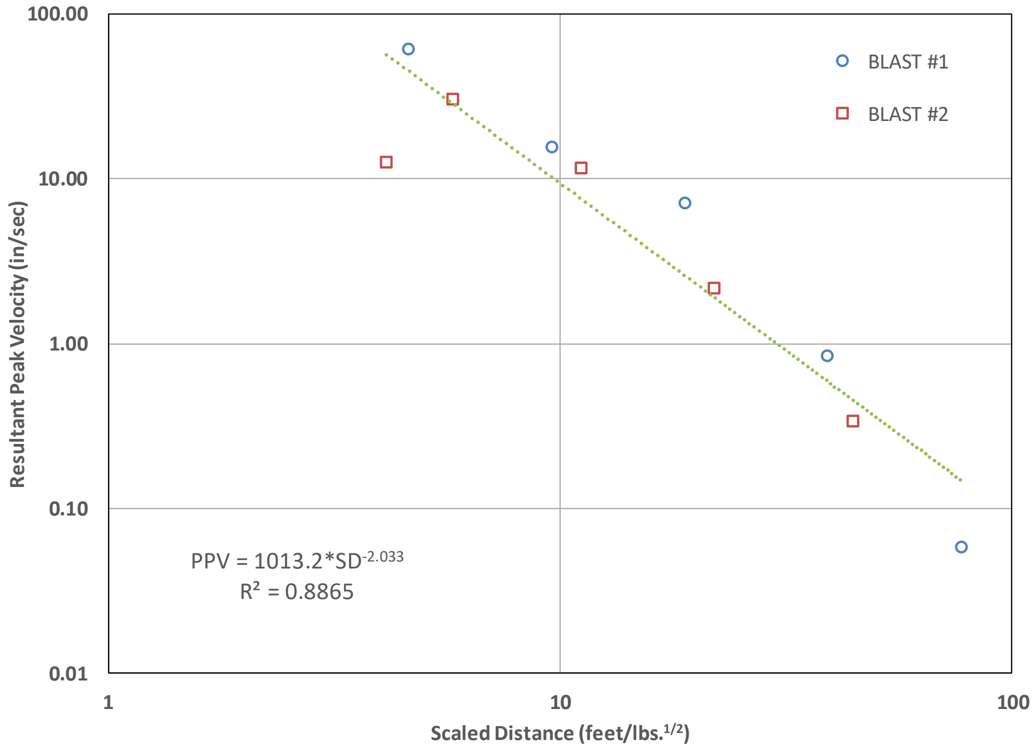

Figure 5. PPV Attenuation in the Concrete Spillway Chute Slab.

Peak compression and tension strain values were extracted from the strain time history records on the main spillway slab. Figure 6 shows the relationship between peak strain and distance from the blast source, where positive strain indicates compression and negative strain indicates tension. Figure 7 illustrates the exponential decrease in resultant PPV with distance from the blast area. Trends shown in Figure 6 indicate peak strain below 100 microstrain at distances greater than 25 feet and negligible strain beyond a distance of 100 feet. It should be noted that these trends represent general observations, and a peak strain value of 100 microstrain would generally calculate well below a typical allowable stress level for reinforced concrete.

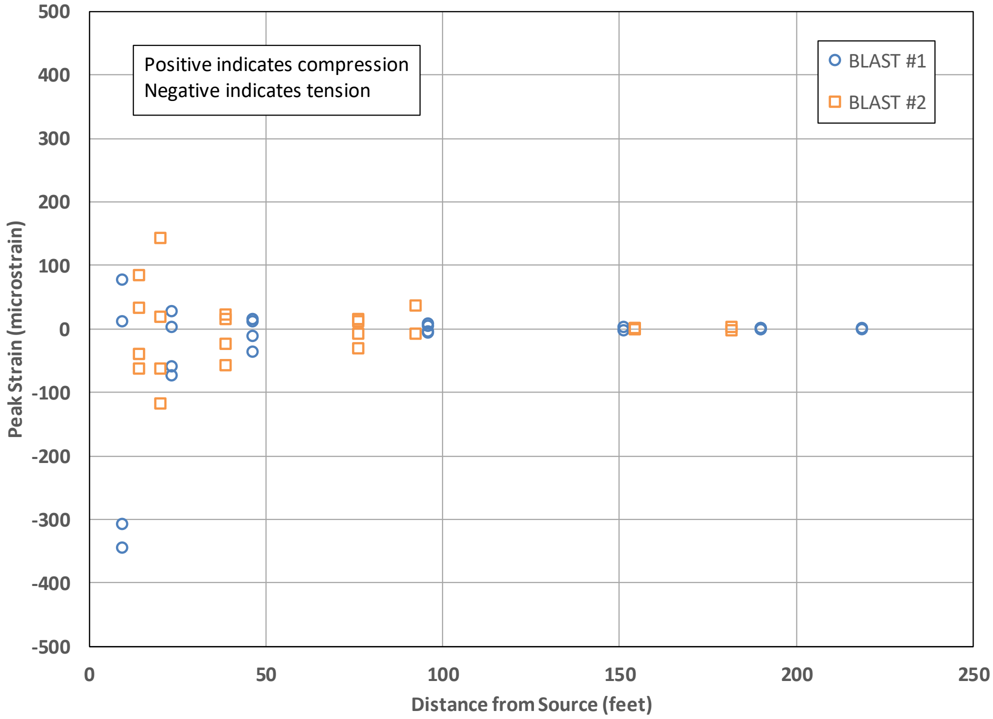

Figure 6. Peak Strain and Distance from Blast Area.

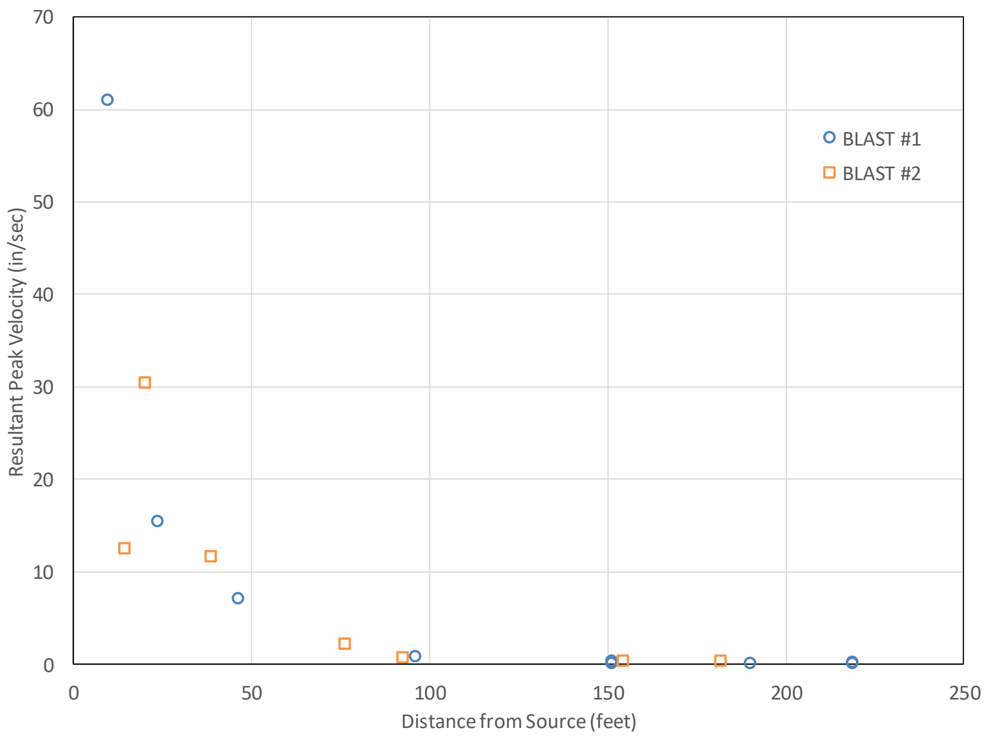

Figure 7. PPV and Distance from Blast Area.

Strain measurements provide a direct way to calculate changes in stress in the concrete main spillway. Figure 8 shows the relationship between peak strain and PPV. Strain relationships shown in Figures 6 and 8 should be considered as characteristic of a concrete slab on grade type structure similar to the subject spillway chute. Results of linear regression relationships are provided on each plot together with R-squared values.

A majority of the data collected includes strain below 100 microstrain. A maximum strain gage reading of 345 microstrain was recorded together with a PPV of 55 ips at a distance of 9.5 feet from the closest blast hole. Additional data points above 100 microstrain would improve the understanding of the linear regression relationship shown in Figure 8.

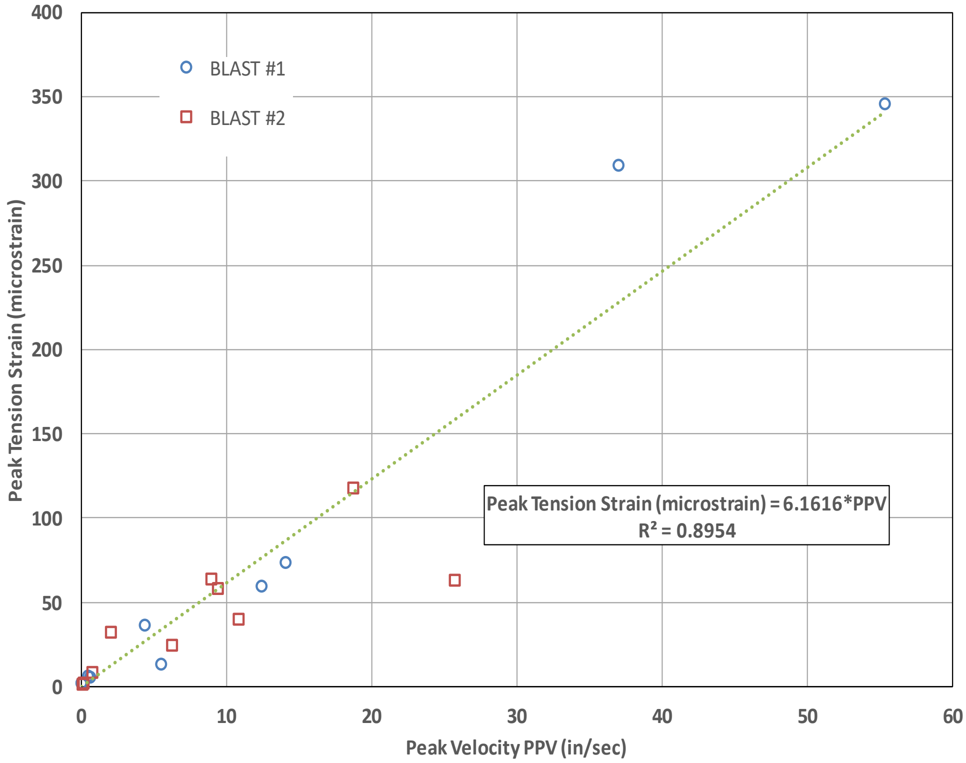

Figure 8. Peak Tension Strain and PPV.

Figure 9. Exposed expansion/contraction joint 18-inches from the nearest blast holes.

Results from all monitoring locations with side-by-side strain gages and accelerometers were assembled and organized into three categories based on peak strain levels: a) 0 to 50 microstrain, b) 50 to 100 microstrain, and c) 100 to 350 microstrain. Figure 10 shows PPV and dominant frequency for each strain level category. The relatively small number of data points above 100 microstrain should be noted. Based on the results observed at the Oroville Dam Spillway, no PPV levels below 16 ips were associated with strain levels exceeding 100 microstrain. Specified vibration limits for all blasting at Oroville Dam for concrete aged 10 days or more included a 10 in/s PPV limit and a peak displacement limit of 0.03 inches as shown on Figure 8 for reference. The Oroville Dam criteria (Gray dashed line) includes no peak strain recordings above 100 microstrain. As shown on Figure 9, no visible damage was observed in concrete located at or beyond a construction joint located just 1.5 feet from the closest charges. As indicated earlier, very light decoupled charges were used in the closest holes to prevent direct rupture damage.

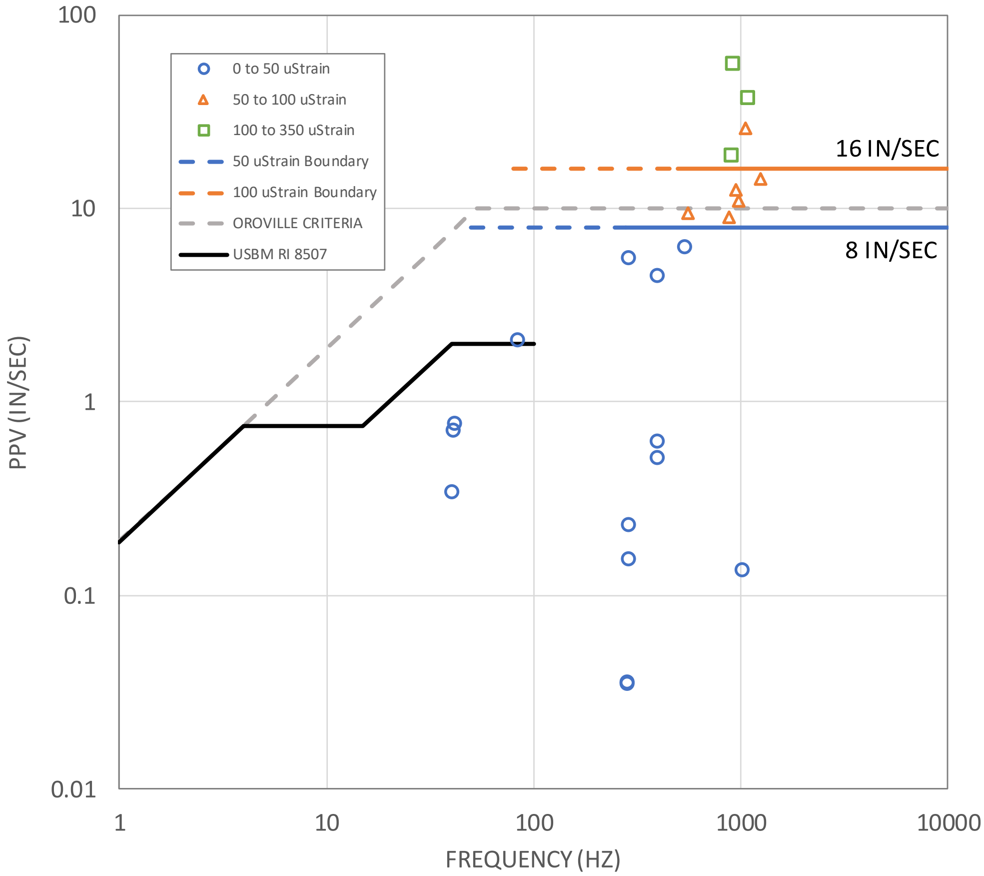

Figure 10. Observed PPV and Frequency at Various Peak Strain Levels.

V. CONCLUSIONS

The controversy regarding what damage criteria is appropriate for reinforced concrete structures subject to nearby blasting events can only be enlightened through an increased knowledge base of strain, motion and frequency recordings. The use of PPV limits established decades ago to prevent dry wall and plaster damage in residential structures are clearly not appropriate for reinforced concrete structures. This paper suggests a comprehensive approach should include monitoring of strain, PPV and frequency content to characterize dynamic stresses with greater confidence. Based on the test blast data, a PPV of 16 ips correlated to approximately 100 microstrain recordings in flat-lying concrete for this project. The 100 microstrain level is well below the 870 to 1,060 microstrain considered allowable for driven concrete piles and should be conservatively appropriate for the spillway slab where existing stresses before blasting can be assumed negligible. Higher PPV vibration criteria would be appropriate for similar concrete structures and blasting conditions presented in this paper if strain and other appropriate monitoring is accomplished to address limitations associated with PPV results.

Results of this study show that (a) no visible damage to the concrete spillway slab was observed for measured values of PPV up to 55 ips with relatively high dominant frequencies in the range of 300 to 1250 Hz, (b) peak strain decreased exponentially with distance away from the blast sites with negligible strain beyond a distance of about 100 feet, (c) Peak strain (microstrain units) was about 6.2 times PPV (ips units) with an average error of about 47 percent and a maximum error of 169 percent. Future monitoring of motion and strain during blasting will improve the site-specific relationship between peak strain and PPV derived from this study, particularly high peak strain. The small number of data points above 100 microstrain is one limitation of this study. Monitoring strain provides a direct way to estimate peak stresses in concrete structures, eliminates the need to attempt to correlate PPV to structural damage, and allows for a rational way to consider the increased strength of reinforced concrete materials subject to dynamic loading.

VI. References

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John Lemke is President of Geodaq a manufacturer of specialized geotechnical and structural monitoring sensors, data acquisition equipment and web-based software. He received a B.S. degree in Geological Engineering from New Mexico Institute of Mining and Technology and an M.S. in Geotechnical Engineering from the University of Texas at Austin. John is a registered professional engineer and geotechnical engineer in California. John has managed the development of innovative instrumentation products including a MEMS based in-place inclinometer, strain sensors with integrated accelerometers, high-speed dynamic acquisition modules, remote data collection hardware, and fully integrated web-based software solutions. John's recent project experience includes a multi-site remote satellite-based monitoring system for natural gas pipelines using strain gauges, piezometers and in-place inclinometers, real-time wireless vibration and long-term displacement monitoring for the BART tube structure, piezometer installation and well abandonment services for the Chabot Dam seismic upgrade, and an automated static pile load testing system for Caltrans using Geodaq MUXTR hardware and fully integrated real-time monitoring software.

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Gordon first used explosives while working as an underground miner in the Canadian Nickel Mines. He later studied mining engineering and geology at Laurentian University in Sudbury, Ontario. After earning a Bachelor of Engineering Degree, he returned to The International Nickel Company and worked as a Mine Planner and Blasting Research Engineer. In the early 1980's, Gordon joined Atlas Powder Company (later becoming ICI Explosives and now Orica) where he held various sales and technical positions. In 1996, Gordon formed an independent company – now called REVEY Associates -- that provides blast design, training and risk management services to the heavy construction and mining industries. During his career, Gordon has designed blasting programs for hundreds of complex domestic and foreign blasting projects. Gordon has authored many papers about controlled blasting techniques and the successful management at many high-risk blasting projects in North America and Internationally.

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