Vibrating Wire Gages Monitor Dynamic Structural Integrity During Blasting

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Introduction

Measuring dynamic effects on existing structures such as dams and bridges during earthquakes or blasting is frequently done using strong motion detectors. However, a more comprehensive dynamic structural evaluation requires direct measurement of deflection, strain, and pressure changes during dynamic events. Many existing structures have vibrating wire gages already installed that can be used with modifications to the data acquisition systems to provide direct measurement of dynamic displacement, strain, and pressure. The project described in this paper provided the opportunity to demonstrate the feasibility of using vibrating wire technology to measure dynamic effects on existing structures.

Many years of experience with strong motion detectors have provided owners and contractors with a large body of data that relates peak particle velocity to observed structural damage. The accumulated experience, used with site-specific test blast measurements, provides a convenient and reliable method of controlling damage to existing structures during blasting. However, strong motion detectors provide limited information about the behavior of a structure under dynamic loading. It is difficult, even with the use of complex numerical models, to evaluate dynamic deflection, strain, and stress changes in a structure from strong motion detector data alone.

Vibrating Wire Gages

Existing gage technologies and high-speed, high-capacity data acquisition and computer systems make it possible today to make direct measurements of structural changes during dynamic loading. This approach was proposed by one of the authors (*Feldman, 2002*) and is being used during construction blasting for a Fish Bypass Facility at Howard A. Hanson Dam (HAH Dam) in western Washington.

The direct measurement instrumentation system being used at HAH Dam is primarily based on vibrating wire gage technology. There were several reasons for selecting vibrating wire gage technology rather than, say, resistance or fiber optic gage technology. The first reason is that the HAH Dam project provided an opportunity to demonstrate the viability of using vibrating wire gages to measure dynamic effects. Many older structures, particularly concrete dams, have numerous vibrating wire gages installed. Those structures with gages cabled to a central location could be outfitted with a system similar to that used at HAH Dam. Other hardware may exist that would allow structures with networked or radio transmission systems to be similarly modified. Obtaining direct dynamic measurements from existing vibrating wire gages would be a valuable addition to data from strong motion detectors. The second reason is that the same vibrating wire gages can be used for both dynamic and long-term static measurements, which may not be the case with resistance gages, and, finally, vibrating wire gage systems are relatively less expensive than fiber optic gage systems.

Vibrating wire gages have been used for many years for static measurements of deflection, strain, pressure, and force changes and have proven to be reliable and stable for long-term applications (*McRae*

1991). Static measurements of deflection, strain, pressure, or force refer to measurements of long-term effects, such as temperature change, that can be adequately evaluated using readings taken at intervals measured in hours or even days. For most static applications, vibrating wire gages are fitted with a single coil that is used to both excite and read the gage. A single-coil vibrating wire gage requires about two seconds to excite and to read, but can be modified by the addition of auto-resonance electronics to monitor dynamic events of up to 20 cycles per second (Hz). The auto-resonance device continuously excites the wire and simultaneously measures the wire frequency. Double-coil vibrating wire gages (continuously excited by the first coil and continuously measured by the second coil) have also existed for many years and can be used to monitor dynamic events of up to 100 Hz.

Experience has shown that even when continuously excited for long periods, vibrating wire gages remain stable. For example, the Norwegian Geotechnical Institute (NGI, *DiBiagio, 2003*) reports that a number of vibrating wire gages have been continuously excited for more than 27 years with no failures of either the gages or the excitation electronics. Zero drift of the NGI gages is reported to average less than 0.5% of full range with gage stresses as much as 25% of the yield strength of the wire.

As noted above, other technologies are available that may be better suited to future dynamic measurements. For example, Fabry-Perot fiber optic sensors can measure a much wider spectrum of vibrations than vibrating wire gages. The drawback of this technology today is that it is more expensive than vibrating wire gages, and fiber optic gages do not have the long history of use and acceptance that vibrating wire gages enjoy. These limitations undoubtedly will be overcome with future use.

Project Description

Howard A. Hanson Dam is a U.S. Army Corps of Engineers (USACE) flood control dam located near the headwaters of the Green River in King County, Washington. The dam is located in a closed watershed that is a primary water source for the City of Tacoma, Washington. The dam, completed in 1961, is an earth- and rock-fill structure with a crest length of 675 feet (204 m) and height above bedrock of 235 feet (72 m). The foundation and abutment rock is highly variable, fractured andesite. The dam is 960 feet (292 m) wide at the base and 23 feet (7 m) wide at the crest and has a reservoir capacity of 106,000 acre-feet (~131 million m^3). The outlet works for the dam consist of a spillway, gate tower, and a multi-pier bridge running from the dam crest to the gate tower, all constructed of reinforced concrete (see Photograph 1). A reinforced concrete lined outlet tunnel extends 900 feet (274 m) from the gate tower to the spillway. The 19 foot (6 m) wide horseshoe-shaped outlet tunnel is supported by steel sets and lined with concrete.

As part of the HAH Dam Additional Water Storage Project, a fish passage facility is being constructed adjacent to the existing gate tower, bridge, and outlet tunnel. The excavation for the facility is being advanced through bedrock using controlled drill-and-blast techniques. The excavation will be immediately adjacent to the gate tower walls and as close as 26 feet (8 m) to the outlet tunnel. The excavation is just to the right of the structures shown in Photograph 2. It is essential that normal and emergency operation of the dam continue throughout construction of the new facility. In order to ensure the functional integrity and safety of the existing structures, the USACE retained Shannon & Wilson to design an instrumentation system that would monitor both dynamic and static impacts of the new construction. Shannon & Wilson also participated in the installation of the instrumentation system and is currently monitoring the performance of the system and structures.

Photograph 1 Howard A. Hanson Dam (*USACE, undated***)**

Photograph 2 Excavation Area (*Shannon & Wilson, 2004***)**

Instrumentation System Development, Installation, and Testing

The instrumentation system for the HAH Dam project was developed at Geokon Inc. under the direction of Shannon & Wilson. A test program was undertaken at Geokon's facilities to evaluate the design of the auto-resonance electronics, the performance of a high-speed data acquisition system, and to demonstrate that vibrating wire gages could accurately and repeatedly measure dynamic input motions. The tests were performed using a double-coil strain gage and a double-coil crack meter, which were displaced at known amplitudes and frequencies. Results of the test program confirmed that the gages, auto-resonance electronics, and data acquisition system would be able to accurately measure and record amplitudes and frequencies in the range expected during blasting at HAH Dam. The dynamic response to blasting of the existing structures was expected to be in the range of 20 to 70 Hz.

The automated data acquisition system (ADAS) selected for the project is a 64-channel DataQ Model DI-760, which has a total sampling capacity of 250,000 samples per second. Theoretically, every channel could be sampled at approximately 3,900 times per second. In practice, some over-sampling is required and it is not necessary to measure frequencies of 70 Hz or less at such high rates. Preliminary field-testing indicated that an over-sampling ratio of 5 with a nominal sampling rate of 300 samples per second would be sufficient to measure the expected frequencies.

The type, range, and location of instruments for the HAH Dam project were selected based on the results of an extensive investigation of the site geology and groundwater conditions, dam construction records and performance history, and numerical modeling of the effects of excavation on the foundation rock and existing structures. More than half of the instruments installed are designed for both dynamic and static measurement.

Dual Purpose Dynamic Gages

The dynamic gages were installed at HAH Dam to obtain direct measurements of amplitude and frequency during a 35 second window that spans the blast event. Immediately after each blast, all dynamic data is reviewed to determine if any of the preset threshold or limit values for each gage type have been exceeded. Threshold and limit values were set during the instrumentation design phase. Threshold values were defined as acceptable levels of displacement, strain, or stress change during blasting. Any measurements that exceed threshold values are cause for further investigation of potential unsafe conditions. Limit values were defined as unacceptable levels of displacement, strain, or stress change during blasting. Any measurements that exceed limit values are cause for modifying or stopping further blasting. The dual-purpose instruments include crack meters, joint meters, surface-mounted strain gages, sister-bar gages, and piezometers.

The crack and joint meters are mounted across construction joints and existing cracks in the outlet tunnel and bridge piers and across expansion joints on the bridge deck. The purpose of the crack and joint meter deflection measurements is to determine displacement amplitude and frequency response during blasting and to identify potential permanent displacements after each blast.

Strain gages are surface-mounted on the concrete walls in the gate tower. Ideally, strain gages would be mounted on reinforcement bars embedded in the concrete to avoid the uncertainty associated with estimating the elastic modulus of concrete and to avoid the potential influence of concrete cracks on measurements of strain. However, in this case, the reinforcement bars were too deeply embedded for gage mounting. The strain gage measurements are used to evaluate strain amplitude and frequency response during blasting and to identify potential permanent strain changes after each blast.

Vertical seismic retrofit anchors were installed on the intake structure attached to the gate tower as part of the current construction project at HAH Dam. The anchors are designed to improve the dynamic integrity of the intake structure during the current construction blasting and during potential future earthquakes. Sister-bar gages were attached to the steel anchor rods and grouted with concrete. Sister-bar gages were installed to evaluate strain amplitude and frequency response during blasting and to identify potential permanent strain changes after each blast.

Piezometers were placed at three levels in two boreholes in the rock mass between the excavation and the existing structures. The piezometers were installed to monitor the effectiveness of the excavation dewatering system. Uncontrolled groundwater in the rock mass could have adverse effects on the stability of the excavation slopes. The piezometers are read dynamically to evaluate the viability of measuring dynamic water pressure changes with vibrating wire gages and to gain some insight into the effects of blasting on groundwater pressures in fractured and jointed rock.

In addition to the direct measurement gages, several conventional geophones are installed at HAH Dam to provide particle velocity and frequency response data. The geophone measurements were used during test blasting to set parameters of charge weight and distance and are now being used for comparison to direct measurements.

Static-Only Gages

The measurements obtained from the static-only gages are used (along with static data obtained from the dynamic gages) to evaluate long-term effects of construction on the existing structures. Long-term effects can be identified by comparison of current measurements to baseline patterns of gage response. Threshold and limit values were defined for static measurements as well. The static-only gages consist of extensometers, in-place inclinometers, and two liquid level systems. The in-place inclinometers are based on electro-level sensors rather than vibrating wire technology. Thermistors installed in both dynamic and static-only gages are also read in static mode only.

Extensometers and in-place inclinometers are installed in the rock mass between the new excavation and the existing structures. These two types of instruments are used to monitor potential movements in the rock mass. Small movements of the rock mass have the potential to affect the performance of the existing structures and large movements could be catastrophic.

Liquid level systems are installed at the base of the gate tower and at one bridge pier to measure differential settlement of each structure. A liquid level system consists of an open channel pipe, half-filled with a water/antifreeze mix, and several liquid level gages. At HAH Dam, the liquid level gages are mounted at the four corners of each structure. A benchmark gage was also installed on the rock surface some distance from each structure. Each liquid level gage consists of a float suspended from a vibrating wire force gage. The float sits in the open-channel water so that any change in water level creates a proportional change in force in the vibrating wire gage, which is then converted to displacement (a more detailed description of a liquid level system can be found in *Feldman, Ellis, et al, 199x*). The liquid level systems installed at HAH Dam can measure differential settlements with an accuracy of ±0.01 inches (±0.25 mm).

Ambient air temperature and reservoir elevation measurements from other instrumentation systems at HAH Dam are also collected and incorporated into the existing structures instrumentation system. Daily and seasonal temperature changes and reservoir elevation changes are the primary external forces that can act on the dam structures.

Data Acquisition, Data Management, and Data Presentation

Static data is collected from all gages each hour and from the dynamic gages during each blast. The dynamic data collection procedure is started approximately five seconds before the blast and allowed to run for 35 seconds. The dynamic data collection procedure samples each gage simultaneously 300 times per second with an over-sampling ratio of five. The over-sampling averages out some of the noise inherent in dynamic data. In addition, static data is collected at ten minute intervals for a 30 minute period immediately preceding each blast and immediately following each blast to provide an additional assessment of potential permanent change due to blasting.

The software used to operate the instrumentation system is MultiLogger provided by Geokon, Inc. The software is used to schedule and collect data from all gages except the geophones. Once the data are collected it is converted to engineering units by means of IDMS, a Microsoft Access application written by Shannon & Wilson. Data is then transmitted to an Oracle database on a USACE web server. Once on the web server, the data are accessible, via a standard web browser, to USACE personnel, the construction contractor, structural engineering consultant, and Shannon & Wilson personnel. Static data is generally available on the web 10 to 15 minutes after reading and dynamic data, including peak values and threshold and limit flags, are available 30 to 45 minutes after each blast. Data can be viewed in several tabular or graphical formats.

Measurements

The HAH Dam instrumentation system for the existing structures has been in place since March 30, 2004. Static readings have been obtained hourly from all gages connected to the ADAS. In the sixteen-plus months of service, about 85 percent of the potential static data has been collected and stored. There have been several short-term incidents related to power or network issues that have caused the ADAS and related software to go offline for as much as 24 hours at a time. The incidents have typically occurred at night or over a weekend when the instrumentation system, power, and communications network are not regularly monitored. However, no data has been lost due to issues related to the ADAS, software, or databases. Static data is reviewed daily to evaluate the performance of the structures and the instrumentation system by examining time history plots of the results from each gage. A summary table of static data is also available on the web site that compares the most recent hourly results to threshold values and to historical minimum and maximum values. More detailed analyses of the static results, including evaluation of seasonal temperature effects and other long-term changes, are prepared periodically for the USACE.

Between May 2004 and April 2005, there were 34 construction blasts. Dynamic data was successfully recorded during each blast. In order to effectively evaluate all of the dynamic readings from each blast in a timely manner, summary tables of key dynamic results from the vibrating wire gages and the geophones were developed for presentation on the web site. The primary vibrating wire gage summary table includes peak minimum and peak maximum values, threshold values, peak values as a percent of threshold, and dynamic offset, if any, from the beginning to the end of each blast. A secondary summary vibrating wire gage table is used to compare pre- and post-blast static results to results recorded during a single blast. The geophone summary includes triggered status (yes/no), acceleration, peak particle velocity, and an approximate response frequency. The primary vibrating wire and geophone summary tables can be sorted by date or by gage for comparisons among gages or for evaluation of results at a given location over time. Time history plots of the results from all vibrating wire gages and geophones are available for review on the web site. More detailed analyses of the dynamic results, including evaluation of gage response versus scaled distance (distance to blast divided by the square root of charge weight) and frequency response analysis by Fourier methods, are prepared periodically for the USACE.

Static Results

Sixteen months of hourly static readings have provide ample opportunity to define baseline performance characteristics of the HAH Dam structures. Although blasting began shortly after the instrumentation system was installed, the blasts to date have been relatively small. With the possible exception of two surface-mounted strain gages, there is no evidence in the static measurements of permanent changes to structures due to the 34 blasts that have occurred to date. Consequently, it has been possible to define good baseline measurements of displacement, strain, and pressure changes. As expected, baseline changes in the existing structures are small and predominantly related to temperature changes.

Seasonally, temperatures at the site range from approximately 24 to 98 °F (–4 to 37 °C). Daily temperature ranges vary ±5 to ±10 °F (±3 to ±6 °C) from the daily average temperature. The annual reservoir elevation change is about 70 feet (21 m). The only effects of reservoir elevation change appear to be on the temperature response of gages that are under water for part of the year and a slight tilting of the gate tower. The static piezometer measurements indicate that the groundwater in the rock between the existing structures and the new excavation are not influenced by changes in reservoir level. The isolation between the groundwater in the foundation rock and the reservoir has been verified by other groundwater measurements and tests at the site.

Dynamic Results

Since the concept of direct measurement of dynamic response during blasting was unproven, the geophones installed on the existing structures at HAH Dam were used during the test blasting phase to establish a site-specific relationship between peak particle velocity and scaled distance. The geophone measurements of peak particle velocity from the test blasts and all subsequent production blasts are shown on Figure 1. The upper bound of particle velocities determined from the test blasts and the pre-set threshold particle velocity are also shown on this Figure. The best-fit relationship between peak particle velocity and scaled distance (green curve) is based on all data. The best-fit line and the upper bound estimate are essentially parallel (on a log-log scale) indicating that production blasting conditions are similar to conditions during test blasting.

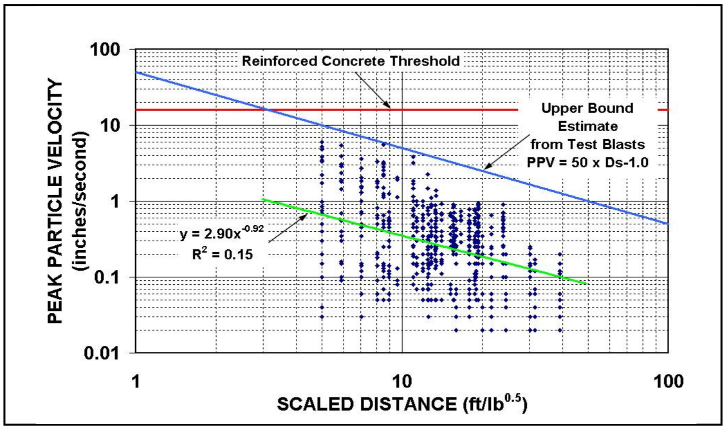

Figure 1 Peak Particle Velocity vs. Scaled Distance, Geophones

A time history plot from one of the geophones is shown on Figure 2. The geophones, when triggered, typically show the duration of the blast effect to be less than one second. The geophones continue to be monitored for comparison to the established particle velocity limits and for comparison to the direct dynamic measurements.

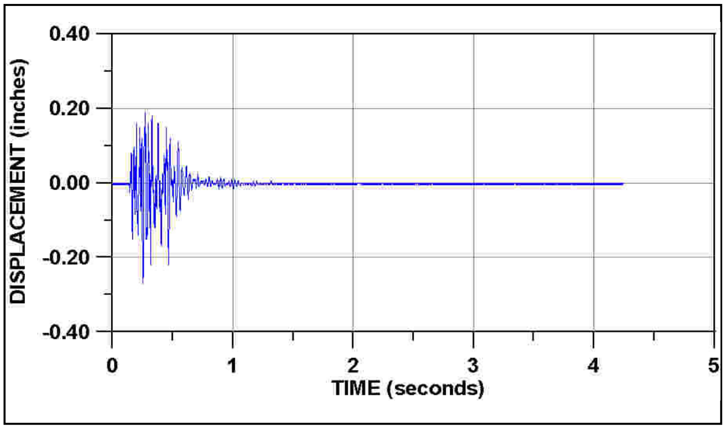

Figure 2 Time History, Geophone

The results obtained from direct dynamic measurement of structural response during blasting are encouraging. The instrumentation and data systems have performed up to expectations and the dynamic measurements have been consistent with the location and type of gage relative to the blast charge weight and distance from the blast. The structural response frequency determined by direct measurement has generally been consistent with frequencies obtained from the geophone measurements.

The peak dynamic displacements measured by the 19 crack and joint meters vary depending on gage location. Crack and joint meters mounted on the interior surface of the outlet tunnel have shown little or no effect of the blasts. Since the tunnel is completely surrounded by the rock mass, the tunnel crown is at an average elevation of 1050 feet (318 m), and the blasting to date has been above elevation 1150 feet (348 m), the lack of dynamic response in these gages is to be expected. As the excavation advances to it final depth at elevation 1020 feet (309 m), we anticipate that the blasting effects on the tunnel will increase. Crack meters mounted on the surface structures have responded to the blasts, but the magnitude of the peak displacements have been too small to correlate well with scaled distance. Joint meters mounted on the bridge deck have shown the largest peak displacement and are reasonably well correlated with scaled distance.

Time history plots for a surface structure crack meter and joint meter for a single blast are shown on Figures 3 and 4, respectively. The noise level inherent in the dynamic measurements can be seen in the lead and trailing portion of the plots. The time history plots generally have a lead of 5 to 8 seconds before the first effects of the blast are recorded. The blast effect in the crack and joint meters generally lasts no more than 15 seconds.

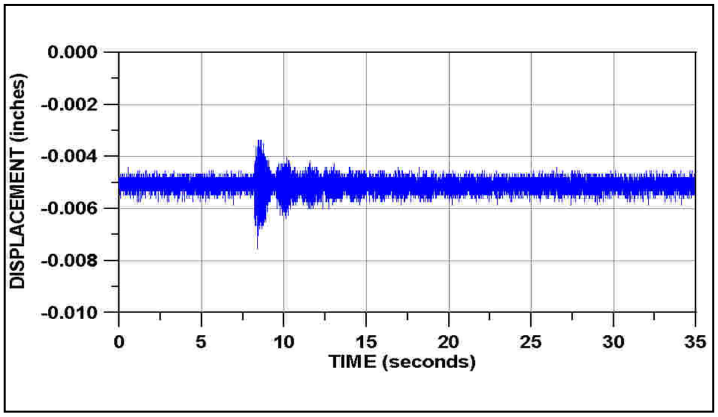

Figure 3 Time History, Crack Meter

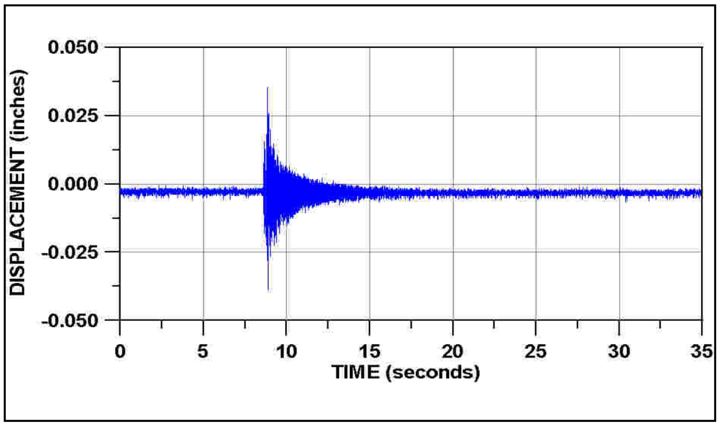

Figure 4 Time History, Joint Meter

There is little or no relationship between peak crack displacement and scaled distance for crack meters mounted on the bridge pier footing nearest the gate tower. These cracks may be shallow and only responding to surface waves, rather than to the overall motion of the structures. The joint meters mounted on the bridge deck, however, show a moderately strong relationship between peak displacement and scaled distance as shown on Figure 5. In all cases, the peak displacements are below pre-set threshold levels.

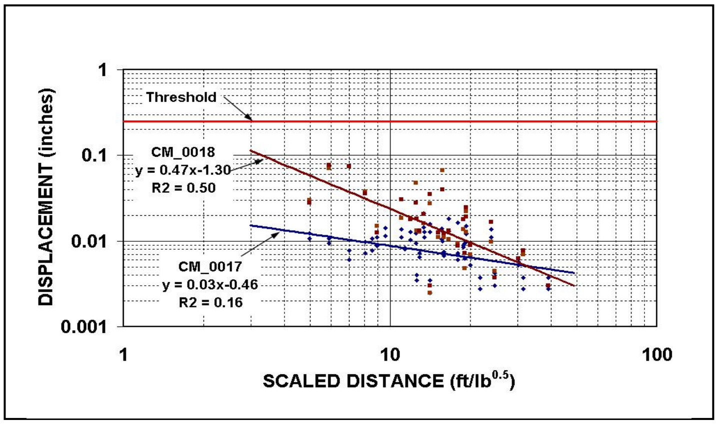

Figure 5 Displacement vs. Scaled Distance, Joint Meters

The crack and joint meter dynamic measurements were also analyzed using Fourier (FFT) methods to determine the frequency response of the structures. However, in addition to the displacement noise that can be seen in the time history plots of crack and joint displacement, in some gages there is an inherent (noise) frequency in the measurements. The inherent frequency may arise from the gage or from the data acquisition electronics. To separate the inherent frequency from the structural response frequency, FFT analyses were made of the initial 5 to 8 second pre-blast portion of the time history and of the entire time history. It was found that the inherent frequency is generally offset from the structural response frequency and varies with the tension in the vibrating wire gage. The response frequency, which is not found in the pre-blast portion of the time history, is consistent from blast to blast. An example of an FFT analysis of several blast records from a crack meter is shown on Figure 6 and the relationship between wire tension and response and inherent frequencies is shown on Figure 7 (wire tension is expressed as displacement on this plot).

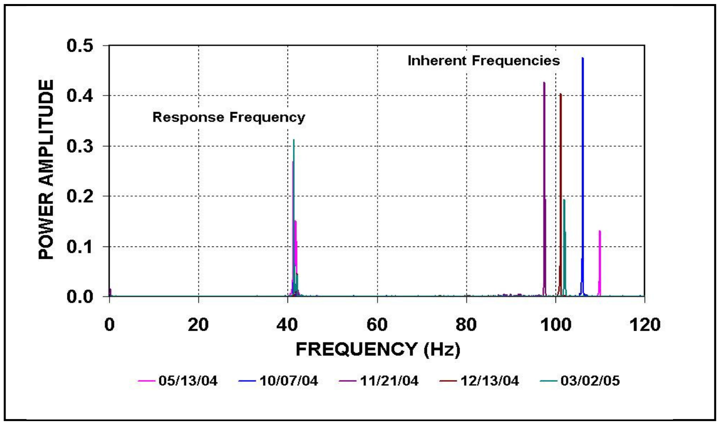

Figure 6 Frequency Analysis, Crack Meter

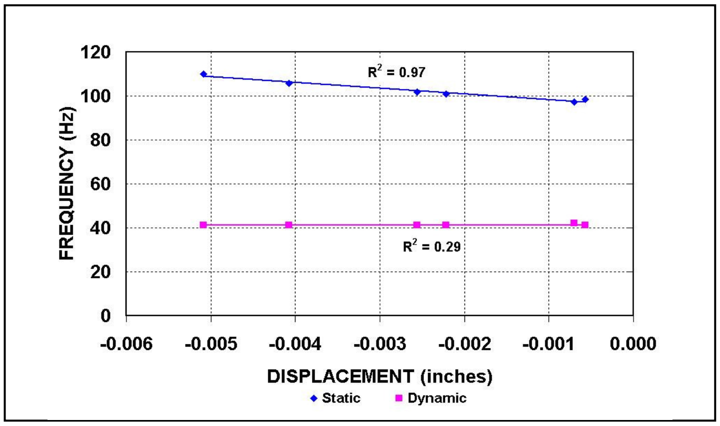

Figure 7 Frequency vs. Displacement, Crack Meter

Response frequencies are distinct and consistent and can be clearly separated from inherent frequencies. Crack and joint meter response frequencies ranged from 40 to 55 Hz, and are consistent with the frequencies determined from the geophone measurements.

The sister-bar gages have provided inconsistent results. As shown on Figure 8, the signal-to-noise ratio for the dynamic measurements is low and the duration of the dynamic effect is short. Since the sister-bar gages are embedded in concrete 25 to 100 feet (8 to 30 m) below the current blasting elevation, it may be the case that future blasts at greater depths will result in a stronger response. In spite of the low signal-to-noise ratio, the sister-bar strain changes are moderately well correlated with scaled distance. Fourier methods have not yet been applied to the sister-bar gage results.

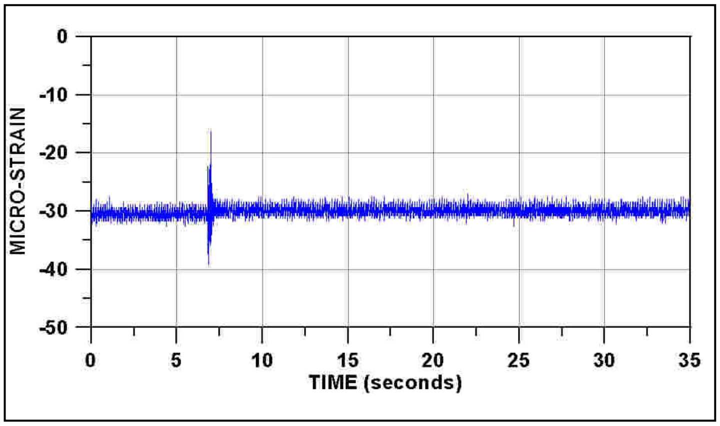

Figure 8 Time History, Sister-Bar Gage

Strain gages mounted on the surface of the concrete structures have responded much like the crack and joint meters. It may be the case that some of the strain gages are responding, in part, to adjacent or near-by micro-cracks in the concrete surface. A typical strain gage response to a blast is shown on Figure 9.

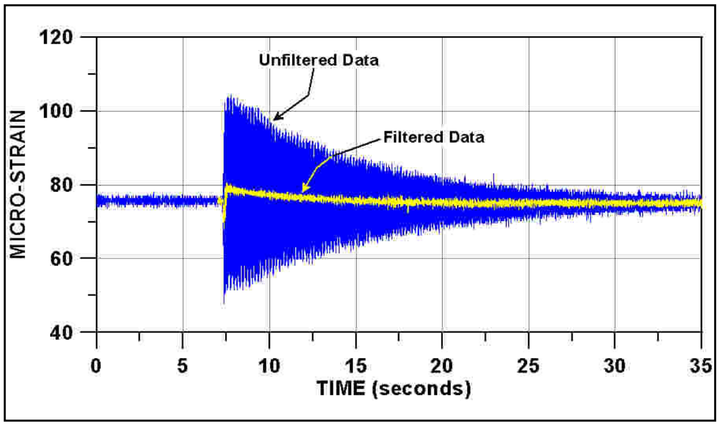

Figure 9 Time History, Surface-Mounted Strain Gage

The dynamic response appears to take 25 or more seconds to damp out. However, as with the crack and joint meters, the strain gages have an inherent frequency that is present in the pre-blast record and the inherent frequency's amplitude is exaggerated during the blast. When the inherent frequency is filtered from the blast record, a much different response is found as shown by the yellow curve on Figure 8. The filtered result appears to be a single cycle of tension and compression, followed by a 10 to 15 second period of relaxation back to the static strain level. The magnitude of the dynamic strain change has a relatively strong correlation with scaled distance.

The dynamic piezometer measurements have followed a consistent pattern of a very rapid change for a duration of less than one second after the blast wave arrived, followed by a period of recovery that often extends beyond the 35 second dynamic record. Post-blast static measurements show that the groundwater levels return to pre-blast static levels. This implies that the crack and joint structure of the rock mass was not changed during blasting and, therefore, the integrity of the rock mass does not appear to be compromised. An example of the typical response of the three piezometers in one borehole is shown on Figure 10.

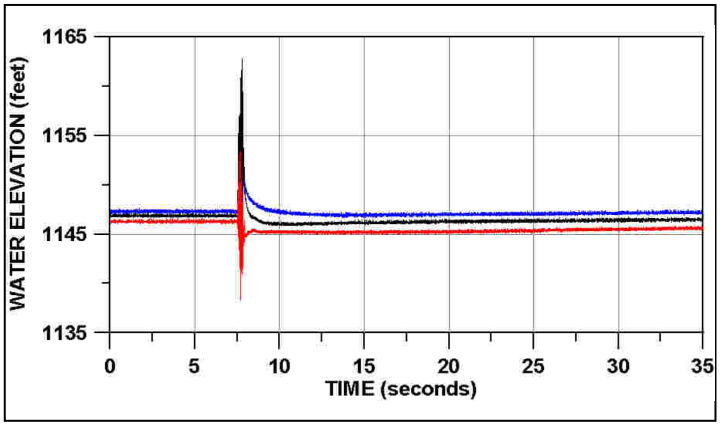

Figure 10 Time History, Piezometers

Only the piezometers in the borehole nearest to the blasting area show a moderately strong relationship between groundwater level change and scaled distance. Since scaled distances are currently computed using the distance from each blast to nearest the structure rather than distance to the piezometer location, it may be the case that a more precise scaled distance calculation would provide a better relationship. Fourier methods were not applied to the piezometer data.

Conclusions and Future Developments

Based on the results obtained during construction blasting to date at HAH Dam, it is clear that vibrating wire gages can be successfully used for direct dynamic measurement of dynamic structural effects with frequencies as great as 75 Hz. The dynamic displacement, strain, and water level changes are generally consistent with scaled distance. The displacements are less than pre-set thresholds. While in situ stresses were not measured, the observed dynamic strain changes indicate that the response of the structures is entirely in the elastic range. Measurements of dynamic deflection indicate that no permanent displacement has occurred, which can be taken as further evidence that the structures remain in the elastic range. Frequency analysis of the measurements has shown that the dynamic response is consistent from blast to blast for each gage and in good agreement with frequencies determine from geophone measurements. The signal-to-noise ratios of the dynamic measurement amplitudes are good given the known static sensitivity and range of the vibrating wire gages. Some questions remain to be resolved regarding frequency noise, especially with respect to the surface mounted strain gages.

The success of the dynamic measurements with vibrating wire gages at HAH Dam suggests that the method can reasonably be applied to other structures with existing vibrating wire gages (either single or double coil). The auto-resonance electronics needed to convert a vibrating wire gage for dynamic measurement have proven to be effective and several high-speed ADAS devices are available. Another possibility under consideration is to develop a portable system of electronics and ADAS that could be used for dynamic testing using either exiting gages or gages installed specifically for the test.

Acknowledgements

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