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Real-Time Continuous Response Spectra Exceedance Calculations

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ABSTRACT: Post-earthquake alarm systems utilize strong-motion data to provide valuable information that enables better rapid decision making during critical and often difficult post-earthquake response. A novel robust approach for providing alarms for large distributed facilities using real-time estimation of response spectra obtained from near free-field motions is presented. The approach can be considered an enhancement on the standard seismic monitoring required for individual nuclear power plants by the Nuclear Regulatory Commission. The inherent scalability, however, affords large scale deployment for multiple facilities distributed across a vast regional area. An influential study dating back to the late 1980's identified spectral response acceleration as a key ground motion characteristic that correlates well with observed damage in structures. Thus, monitoring and reporting on exceedance of spectra-based thresholds are useful tools for assessing the potential for damage to facilities or multi-structure campuses based on input ground motions only. In fact, this type of monitoring is required for all nuclear power plants in the US and globally. Currently, the standard approach is to trigger and record an earthquake event in its entirety, perform necessary post processing (e.g., signal conditioning), compute spectral responses, check for exceedance, and issue alarms accordingly. This approach has worked well for individual plants with a small number of channels. However, it is not scalable or robust enough for system networked with multiple distributed facilities with a larger number of channels (100s). The approach presented here is a simpler, more robust method that continuously and in real-time calculates response spectra exceedance. Details on the novel approach are presented along with an example implementation for a very large energy production company.

KEY WORDS: Response Spectra; Real-Time Continuous Processing; Earthquake Alarms.

1 INTRODUCTION

Post-Earthquake Alarm Systems (PEAS) utilize real-time strong-motion data to provide valuable information that enables better decision making during the critical and difficult immediate post-earthquake response actions. The primary benefits derived from implementing PEAS for a company with large distributed facilities include:

1. Provides confidence in onsite operational personnel to stop hazardous processes preventing costly post-event fires and other related disasters
2. Reduces the risk of overreaction such as unnecessarily shutting down plant functions or initiating evacuations which potentially costs millions of dollars in business interruption
3. Provides immediate and accurate information on the extent to which structures are affected (i.e., potential for damage), which can help decision makers better allocate resources and streamline the emergency response actions

A novel robust approach for providing post-earthquake alarms using real-time estimation of response spectra obtained from near free-field motions has recently been developed and implemented for a large energy producing company with multiple facilities spanning distances over 1500km. The fundamental approach can be considered an enhancement on standard earthquake monitoring required for individual nuclear power plants by the Nuclear Regulatory Commission (NRC).

In 1988, the Electric Power Research Institute conducted a study that set out to determine what constitutes damaging ground motion due to earthquakes and to develop criteria for determining exceedance of what is called the Operating Basis Earthquake (OBE) [1]. In this study, several ground motion characteristics were investigated and trends were established based on observed structural damage for over 250 earthquake histories. The conclusion reached by the study was that a combination of two parameters, peak spectral response pseudo-acceleration (PSA) and cumulative absolute velocity (CAV), is best suited for assessing the potential damage of a given ground motion history.

In 1997 the NRC published regulatory guide NRC-1.166 that provided details on implementation of post-earthquake actions for individual nuclear power plants [2]. This document includes PSA and CAV as well as a new exceedance check using velocity response spectra. The novel approach described here currently implements only the PSA parameter. CAV checks may be included in future development. Basically, if a magnitude 5 or greater earthquake occurs within a 200km radius, a nuclear power plant (NPP) must shutdown unless it can reliably advise the NRC, within four hours, that the earthquake's effects on the plant have not exceeded its OBE or CAV design requirements. To achieve this, seismic instrumentation is installed on NPPs with a monitoring system that can provide automatically generated reports on OBE exceedance immediately after an earthquake.

The standard approach for this process has been to trigger and record an earthquake event in its entirety, perform the necessary post processing (e.g., signal conditioning), compute spectral responses, check for OBE exceedance, and issue alarms accordingly. This approach has worked well for several decades for individual plants with a small number of channels (10 to 20). However, the process it is not scalable or robust enough for an integrated system with multiple distributed facilities across a vast region with a larger number of channels (100s to 1000s).

Rather than rely on event triggers and perform the necessary steps on a event record ex post facto as described above, a novel approach was developed to calculate PSA continuously and in real-time. This paradigm shift provides a much simpler more robust computation algorithm with less potential failure points. For example, the real-time system no longer depends on trigger thresholds which may cause false triggers or worse, miss the event entirely. Sending alert/alarms upon direct exceedance of the specified spectral limits (e.g., design spectra or OBE, etc.) completely removes the risk of false positives stemming from real events.

The remaining sections provide details on the novel real-time approach and present an implementation case study for a large energy producing company.

2 REAL-TIME SPECTRAL CALCULATION AND EXCEEDANCE CHECK

Real-time calculation of PSA exceedance and alarm dissemination are enabled with *Bighorn*, an extension module based on *Antelope* that combines real-time spectral monitoring and alarm capabilities with a robust built-in web display server. *Antelope* is an environmental data collection software package from Boulder Real Time Technologies (BRTT) typically used for very large networks and real-time seismic data analyses [3]. The information flow diagram for *Bighorn* is displayed in Figure 1.

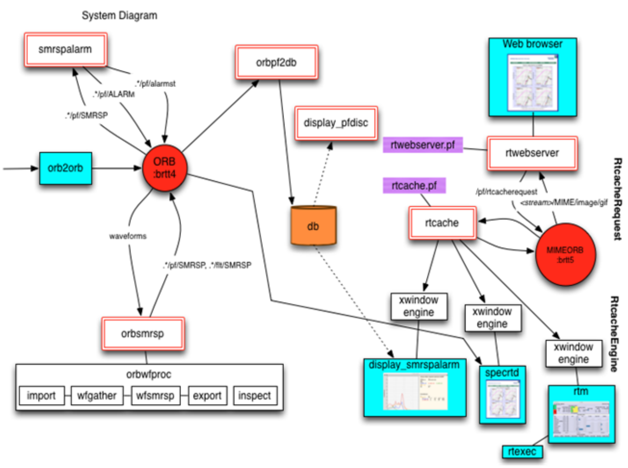


Figure 1. Bighorn layout information flow diagram.

The primary function of Bighorn's engine, *orbsmrsp*, is to produce continuous time-dependent response spectra for incoming acceleration streams. It utilizes expanded floating point data representations within object ring-buffer (ORB) packets and waveform files in the Datascope database system [4]. This leads to a very fast method for computing continuous time-dependent response spectra for a large number of channels. As shown in Figure 1, near-real-time packets of continuous time-series data are processed by the *orbsmrsp* program, which creates response spectra at successive time slices. These response spectra are put back on the ORB as encapsulated data packets. From there they are stored in a Datascope database by the *orbpf2db* program. A Python script *smrspalarm* evaluates these response spectra for exceedence of the specified spectral limits, reporting any such exceedances via alarm packets that are put on the ORB for use by any response processes that need them. The right half of Figure 1 shows the web-display subsystem, which allows alert dissemination, interactive exploration, and alarm cancellation via the world-wide web. This capability is supported by two main programs: *rtwebserver*, which provides an embedded web-server for the Antelope monitoring platform; and *rtcache*, which pre-constructs information products (such as downloadable images of spectral plots) to be served by *rtwebserver*. The remainder of this section describes the response spectra calculation process in more detail.

Response spectra are continuously calculated in real-time by passing the acceleration streams through a set of digital linear recursive filters one for each specified frequency-damping pair. For example, if the acceleration sample rate is 200sps, and a spectrum is defined using 100 frequencies and a single damping ratio, then 100 response spectra streams at 200sps will be created as shown in Figure 2.

Peak response spectra (PSA) values are obtained during a decimation phase according to a specified decimation factor. This is done by assigning the maximum value of the un-decimated response spectra stream over the time window determined by the decimation factor, to the sample value of the now decimated PSA stream. Continuing from the example above with a decimation factor of 100, this process yields 100 PSA streams at 2sps. Maximum PSA values are then obtained over a specified running overlapping process interval. It is these maximum PSA values that are displayed in real-time and compared to the exceedance thresholds. Figure 3 illustrates this 'behind-the-scenes' calculations for three example data channels. The acceleration history for each channel is shown on top with earthquake-like activity occurring at around 19:12. Beneath the acceleration waveforms are instantaneous frequency-slices of color-mapped max PSA values. The frequency is on the y-axis and the warmer the color, the higher the amplitude.

As proof of concept, a known example waveform data set was fed into the system as streaming acceleration. Figure 3 shows the real-time response spectrum (blue) and the spectrum calculated using standard post-event procedures (red). The results from the two methods are indistinguishable.

Depending on what is available for or required with respect to exceedance criteria, spectral thresholds could be in the form of Design Response Spectra (DRS), Maximum Credible Earthquake (MCE), Operational Basis Earthquake (OBE), Safe Shutdown Earthquake (SSE), or even a constant spectral acceleration limit value.

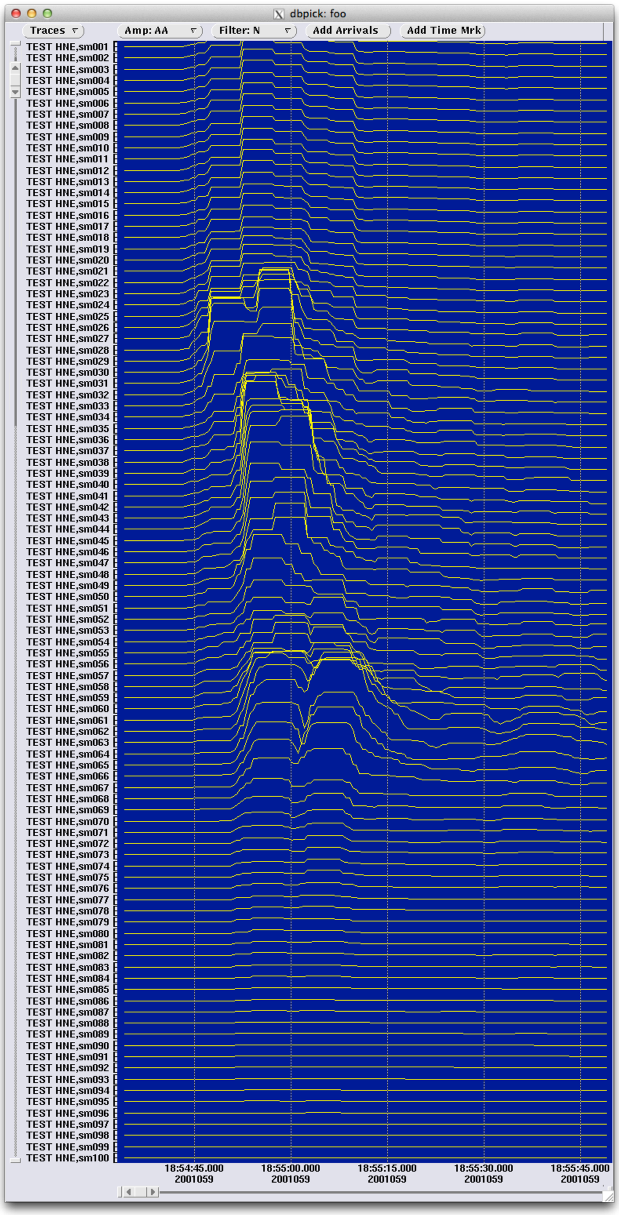


Figure 2. One hundred response spectrum streams created from passing single acceleration stream through set of 100 digital recursive filters.

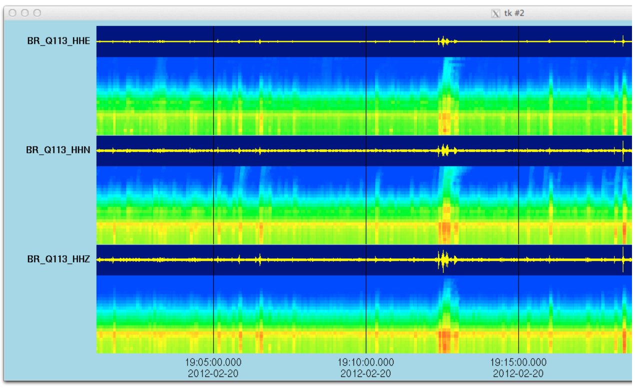


Figure 3. Display of real-time max PSA as color-mapped frequency-slices below acceleration data for three channels.

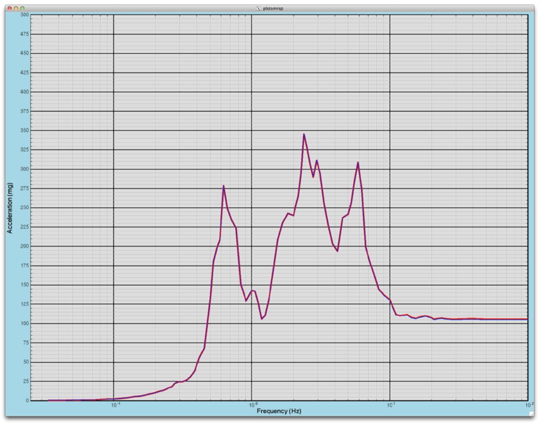


Figure 4. Comparison of spectrum calculated in real-time (blue) and standard post-event procedures (red).

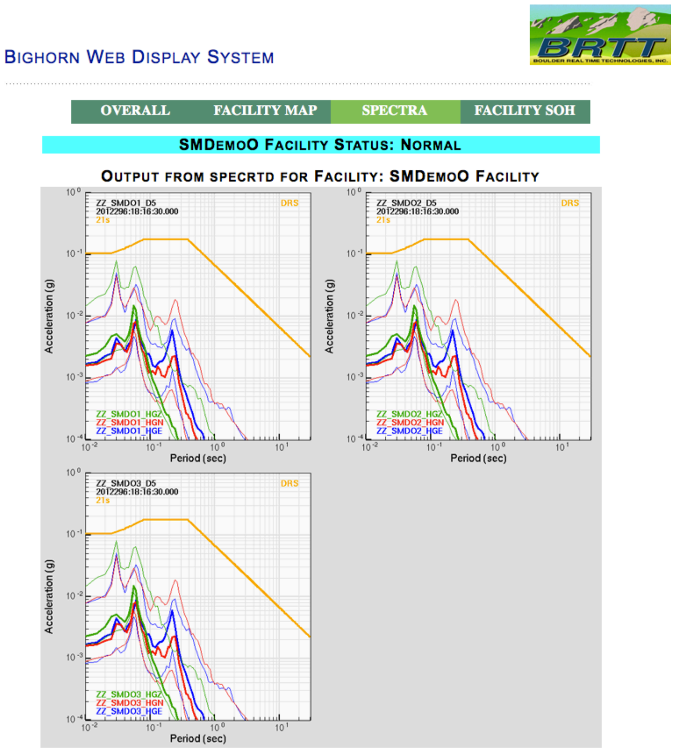
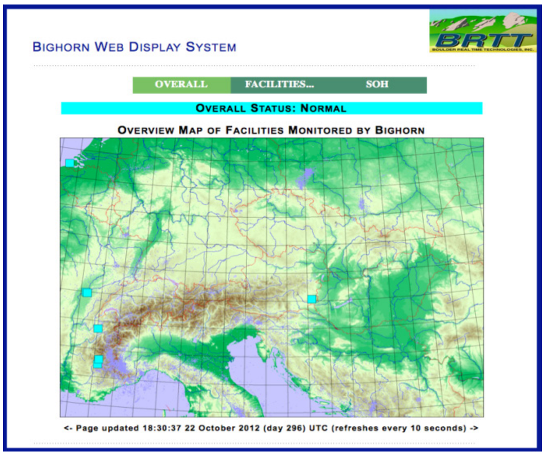


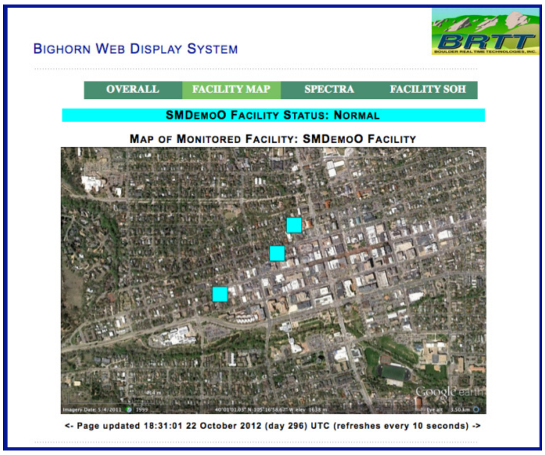
Figure 5. Bighorn web display snapshot of real-time spectral calculations.

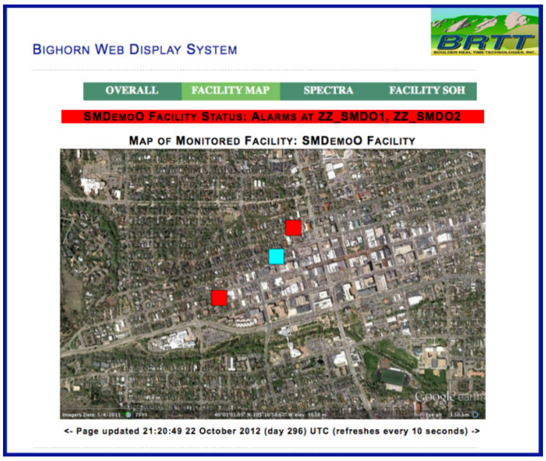
Figure 5 shows the web user interface with a snapshot of the real-time spectral calculations, along with upper/lower excursion limits over a user-specified time window, and exceedance level for three 3-component stations. The real-time color-coded three component spectra are represented with thick lines, whereas the upper/lower excursion limits are thin lines. Although not a primary objective of PEASs, observations of real-time spectra may provide unique insight into the site specific conditions. To the author’s knowledge, such investigations do not exist.

Because the real-time approach is most valuable for an extensive geographical distribution of facilities, the primary display is map-based. Figure 6 displays the Bighorn web server screenshots of an example network overview (top) and facility pages with different alarm state scenarios. The status of a given station is represented by the user-defined marker color. For example, a red-colored box represents alarm exceedance and orange-colored box represents a state-of-health (SOH) issue such as low battery voltage or broken communication. In the event of an exceedance, alarms are issued and an event report is made available – Figure 7.

The event report displays the cumulative response spectra which are equivalent to the post-event calculated spectra – see Figure 4. It also shows the exceedance threshold spectra, the acceleration waveforms, and an event summary. The event summary includes parameters such as peak acceleration, peak velocity, and several exceedance statistics.







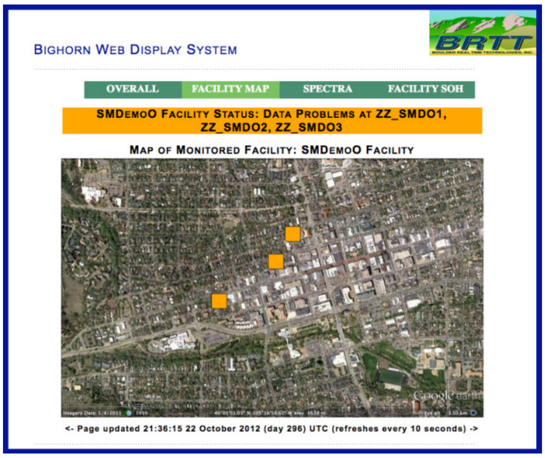
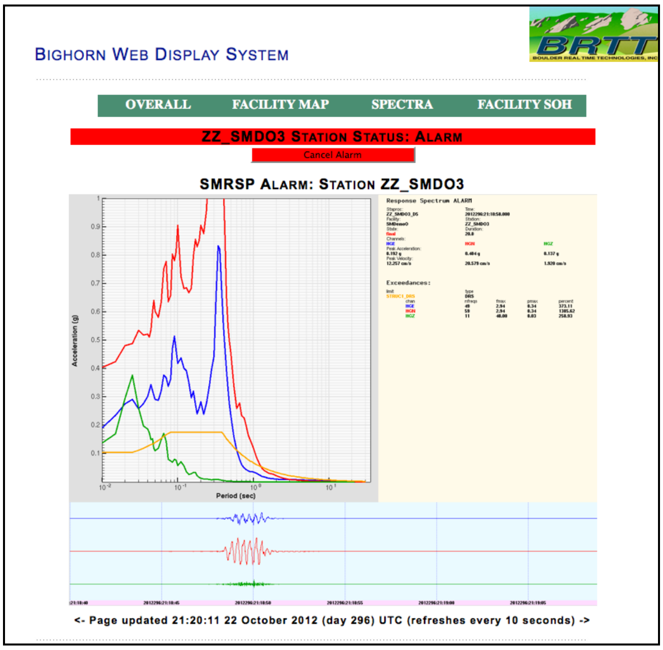
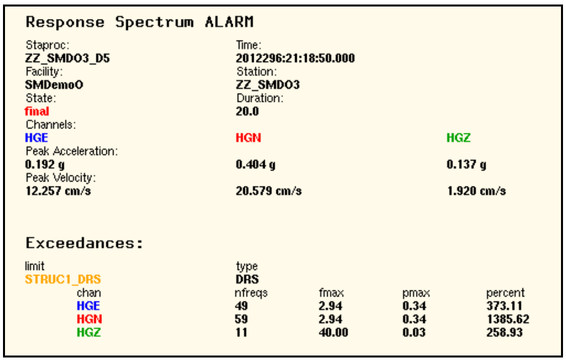


Figure 6. Bighorn web displays, from top to bottom: network overview, facility page, facility page showing exceedance alarm on two stations, facility display showing SOH issue on all three stations.





Response Spectrum ALARM

Staproc:		Time:		
ZZ_SMDO3_DS		2012296:21:18:50.000		
Facility:		Station:		
SMDemoO		ZZ_SMDO3		
State:		Duration:		
final		20.0		
Channels:				
HGE		HGN		HGZ
Peak Acceleration:				
0.192 g		0.404 g		0.137 g
Peak Velocity:				
12.257 cm/s		20.579 cm/s		1.920 cm/s

Exceedances:

limit	type			
STRUC1_DRS	DRS			
chan	nfreqs	fmax	pmax	percent
HGE	49	2.94	0.34	373.11
HGN	59	2.94	0.34	1385.62
HGZ	11	40.00	0.03	258.93

Figure 7. Bighorn web display: event report with zoomed in insert.

An important aspect to consider when implementing a PEAS is how to handle alarm acknowledgement. Bighorn alerts users of an alarm as soon as an exceedance is detected. Earthquakes can last several minutes and so the immediate information displayed is preliminary until the event is over at which point the alarm state is marked as final. Users can clear alarms by confirming acknowledgement of a final alarm.

3 CASE STUDY: A LARGE ENERGY PRODUCING COMPANY

Details on an example case study for a large energy producing company are presented here. Because of a non disclosure agreement, certain details cannot be shared. Photos and figures herein are thus representative and come from similar projects or mock-up systems.

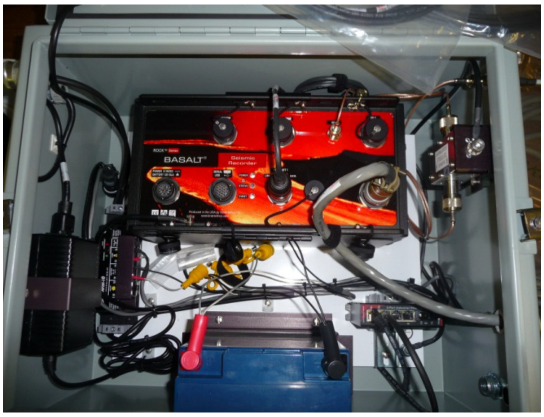


Figure 8. Photos of example earthquake alarm system components, from top to bottom: FFS, FFS with cover open, NEMA4 enclosure open showing Basalt datalogger and peripherals, display work station, central alarm controller and server, row of facility alarm controllers.

Recently, a very large energy producing company with facilities distributed across a sizeable region (spanning 1500km) opted to implement an earthquake alarm system to enable better decision making during seismic induced emergency. The project's vital objectives were to provide immediate alarms and information regarding the extent of potential damage to each facility and to the company's central headquarters. After an expansive survey of globally available options, Kinemetrics' ASPEN solution with Bighorn was awarded [5]. The project scope included outfitting 20+ facilities with a small network of near Free-Field stations (FFS), top photo Figure 8. Each station includes a triaxial accelerometer, Basalt data-logger, power supply system (e.g., battery, solar charger and panels), communication system (e.g., FO media converter, Ethernet device, Wi-Fi, etc), and environmentally protective steel enclosures. The instrument enclosures are mounted to a small (1m x 1m) concrete pad that is well anchored to the ground. The entire station is housed in a fiberglass hut for an additional layer of protection against vandalism and the extreme environment. The stations are networked on the company intranet along with a facility-alarm control cabinet that provides local onsite alarms, see bottom middle photo in Figure 8. Each facility-alarm controller cabinet contains an alarm relay panel, a Marmot field processor, an MRV terminal server, and a UPS.

A central alarm controller and server collects data from all facilities (50 stations, 150 channels), performs the real-time PSA exceedance calculations, and serves all information and alarms through the *Bighorn* web server, Figure 8. The central alarm controller and server cabinet includes four alarm relay panels, MRV terminal server and Ethernet carrier, and a Dell PowerEdge R910 data acquisition and processing server. Two display workstations with two 22-in touchscreen monitors were provided as well, bottom photo Figure 8.

A schematic of the system network is shown in Figure 9. The green lines show the web client links to the web-server at the operations center. The web-display is facility centric displaying only their applicable web-pages. The red lines are representing a) data acquisition from the remote field processor to the processing server; and b) the alarm packets, to drive the alarm panels at the facility, pushed reliably from the processing server to the Marmot Field Processor by positive acknowledgement.

As the first of its kind and scale, this ambitious project presented the project team with ample challenges and rewards. For example, one of the more challenging aspects stemmed from integrating such an expansive network on to a customer's private multi-region intranet. Although well integrated within the company infrastructure, each facility still had its own managerial team and administrative policies, leading to a new set of security, access, and sometimes contractual issues, at each installation. However, the rewards are numerous and worthwhile. The seismic risk inherent to energy producing companies with distributed yet interdependent facilities is significant. And the immediate post-earthquake decisions are the most important and difficult ones to make during a state of emergency. For example, stopping hazardous processes could prevent costly post-event fires and other related disasters, but unnecessary shutdowns can potentially cost millions of dollars. Having immediate and accurate information, such as the extent to which specified performance limits may have been exceeded (i.e., potential for damage), can provide confidence to onsite personnel charged with making these crucial decisions. Additionally, an understanding of the affected region and structure types (i.e., fundamental periods on the spectrum) can help decision makers better allocate resources and streamline the emergency response actions.

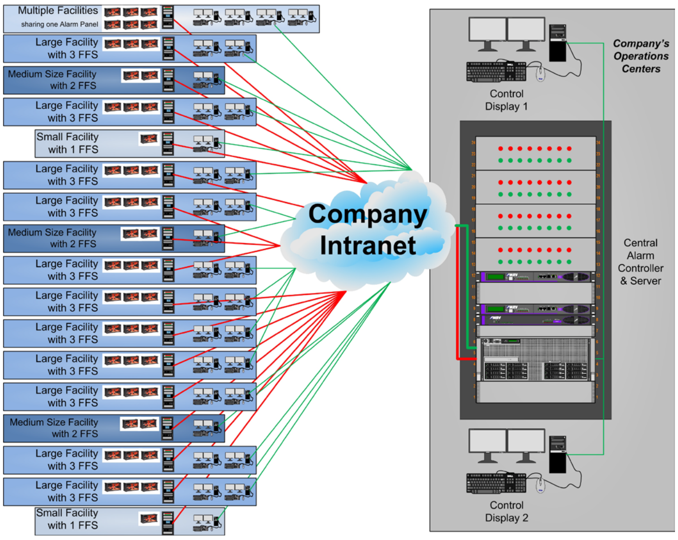


Figure 9. Schematic of system network.

4 CONCLUSIONS

Equations should be centered and the numbering should be right-justified. A post-earthquake alarm system that implements a novel robust approach for providing post-earthquake alarms using real-time estimation of response spectra obtained from near free-field motions was presented. Peak response spectral acceleration exceedance has been shown to correlate well with the potential for structural damage. The *Bighorn* solution described represents a paradigm shift in how strong-motion data is continuously processed in real-time to enable remote alerting of spectral limit exceedance.

A case study was presented which included system implementation details along with project challenges and rewards. The project's successful results allow the customer to utilize immediate and accurate information to enable better decision making during seismic induced states of emergency.

Future work includes expanding the approach to enable CAV check and integrating structural response data, from structural health monitoring systems, into the overall emergency management and post-event action plan

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