Enhanced Rapid Post-Event Assessment of Buildings

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ABSTRACT: Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions, and nuclear power plants, cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Consequently, several leading technology and engineering consulting firms have teamed up to offer an Enhanced Rapid Post-Event Assessment service built upon utilizing the timely information afforded by structural instrumentation aimed to avoid unnecessary evacuation and shutdown and/or minimize expensive downtime. San Francisco, for example, and several other forward-thinking jurisdictions have established Building Occupancy Resumption Programs (BORP) that permit the building's "engineer-on-call" to be pre-deputized to perform the ATC-20 Red/Yellow/Green tagging of the building in lieu of official inspectors. Structural monitoring is a natural fit to these programs since engineers are assigned to a building in advance and thus already familiar with the building and its structural characteristics. The real-time monitoring systems provide intuitive onsite display, alerting, and remote notification on exceedance of demand/design parameters such as interstory drift, absolute acceleration, and response spectra. This information, which is continuously, immediately and remotely available to building personnel and consultants, is useful throughout all phases of the post-earthquake response, inspection, and recovery process. Presented here is an overview of the enhanced rapid post-event assessment solution along with several cases studies.

KEY WORDS: Structural Health Monitoring; Post-Earthquake Assessment; Instrumentation.

1 INTRODUCTION

Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions, and nuclear power plants, cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Hospitals and medical facilities, in particular, have a profound need to maintain building operational status and function in the aftermath of strong earthquakes to allow continued care for current patients and also to receive new patients injured by the disaster [1]. In order to avoid unnecessary evacuations and minimize expensive downtime, a proactive solution to performing rapid, detailed, and accurate post-earthquake safety assessment of these facilities is needed.

Post-event assessment (PEA) refers to the inspection and safety evaluation of a structure following a significant event such as an earthquake. PEA standards and response programs not only benefit building owners and municipality officials, they help to create innovative and proactive solutions for performing rapid and accurate evaluations. San Francisco and several other forward-thinking jurisdictions have established Building Occupancy Resumption Programs (BORP) that permit the building's "engineer-on-call" to be pre-deputized to perform ATC-20 Green/Yellow/Red building tagging in lieu of official inspectors [2, 3]. This has lead to engineering companies offering rapid PEA services. The US Navy independently developed a similar innovative Rapid Evaluation and Assessment Program (REAP) for their west coast hospitals and medical facilities [4]. The common goal among these rapid PEA programs is to formalize and pre-organize the PEA response and process.

Figure 1. Monitoring systems installed in US west coast.

A key aspect in rapid PEA process is the onsite safety inspection. Traditional visual-based inspections can impose high costs and inconvenience on building owners and occupants alike. For example, physical access to structural members usually requires the removal of non-structural components such as interior partitions and fire proofing. The post-earthquake detailed inspection requirements of welded steel moment frame buildings with pre-Northridge Earthquake style connections can be especially time consuming and costly to implement [5]. Prolonging expensive downtime, limited resources such as qualified inspectors may not be immediately available after a damaging event, especially for dense urban areas. Enhanced rapid PEA refers to the services previously described but enhanced by utilizing timely information afforded by advanced structural monitoring systems.

As shown in Figure 1, several buildings along the US west coast have been equipped with permanent monitoring systems as part of an enhanced rapid post-event assessment service offered to building owners from leading engineering consulting companies. The primary goal of the monitoring systems is to provide useful information throughout the PEA process.

An overview of the monitoring system and its integration within the rapid PEA response process is provided in the following section. Several case studies are then presented. Finally, lessons learned from these and other similar projects are summarized.

2 MONITORING SYSTEM OVERVIEW

The monitoring system described here is the OASIS (On-line Alerting of Structural Integrity and Safety) system from Kinemetrics, Inc., Figure 2. The OASIS system is a flexible structural monitoring system that provides for the collection and processing of real-time acceleration, velocity, displacement, and inter-story drift data. The OASIS monitoring system consists of three major hardware subsystems; sensors, data acquisition, and the display and alarm system.

Accelerometers are the sensor of choice due to their robustness and ease of installation. For buildings, interstory drift is the critical response quantity of interest, but since no sensor currently exists that can reliably capture relative story displacements [6], double numerical integration is performed on the real-time acceleration data. This difficult method requires several signal processes such as linear band-pass filtering and is one of the primary functions of the OASIS software.

The central recording unit provides the necessary tools for continuous real-time and event-driven data acquisition such as precise GPS-based timing, power supply and management, signal processing, analog-to-digital conversion, and data file formatting and storage. It also provides the necessary communication interfaces for the PC display and alarm system. Central data recorders, compared to distributed or wireless networks, remain the only commercially viable solution for such demanding applications requiring robust permanent systems. Although running long analog sensor cables can be expensive, wireless technology, while promising, is not yet mature enough. Wireless-power for example is still in technological infancy and probably will be for some time. Thus, replacing analog cabling with wireless technology (or distributed recorders) requires local power supply at each sensor (or recorder) location which in-turn increases upfront costs in both hardware and implementation as well as in maintenance demand. This is especially true considering that sensors are typically located in difficult areas to access such as above ceiling tiles. Another challenge with wireless technology stems from the limited data buffering capacity at the sensor node preventing packet re-transmission leading to permanent gaps data, which may negatively impact overall results and real-time processes.

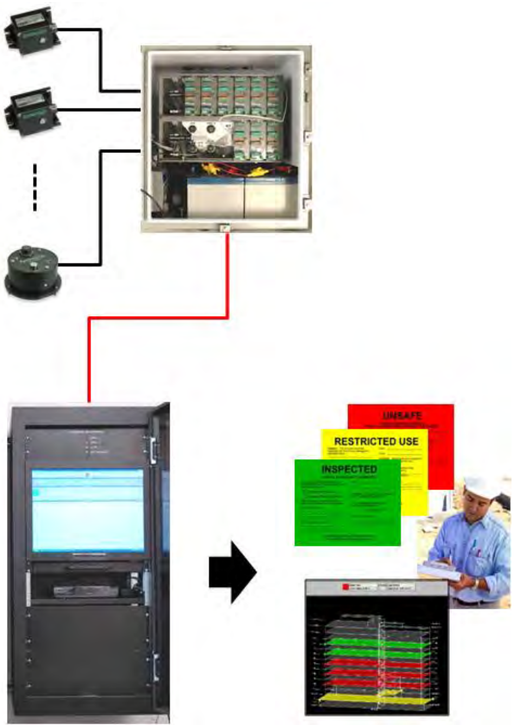
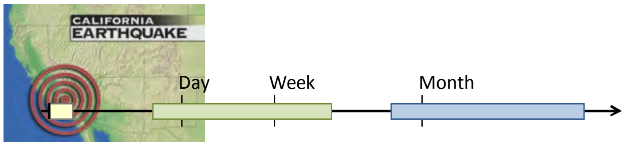


Figure 2. OASIS monitoring system for rapid post-event assessment.

The display and alarm cabinet consists of a rack-mounted industrial computer with Alarm panel, router/firewall and UPS backup power. OASIS software running on the computer is responsible for controlling the alarm panel, performing real-time processes (e.g., double numerical integration), and providing interactive display for user control. A host of notification methods (i.e., email, FTP, SMS, etc.) are available per user discretion.

2.1 *Rapid Post-Event Assessment Process*

A key aspect in the successful enhancement of a rapid PEA process is the integration of the monitoring system within the overall process. Post-event response can be divided into three phases; immediate response, inspection phase, and detailed evaluation, Figure 3. Although different tools are required for the different phases, the information provided by the monitoring system is useful during all three.



Immediate Response

- Onsite response action that occurs immediately after shaking stops
- The natural inclination of occupants is to evacuate after a large earthquake, thus the goal is to ***enable continued occupancy*** and avoid unnecessary evacuation or facility shutdown
- Onsite alarms provide confidence to operation personnel that it is ***OK*** to stay inside and continue business as-usual

Inspection Phase

- Initiated ASAP, but can be few days or weeks depending on extent of regional damage and contractual arrangement
- Building response data are used to aid engineers in the ***inspection and tagging process*** by targeting areas that exceeded predetermined thresholds
- More detailed response analyses can be quickly performed and ***results presented in a brief handout*** to supplement the immediate information provided

Detailed Evaluation Phase

- Extends over a period of months
- Event (and aftershock) data can aid in the subsequent engineering evaluation for assessing potential damage and ***extent of required repairs***. This is particularly applicable for pre-Northridge SMRF's connections which are susceptible to weld fractures that are difficult to detect and expensive to repair
- Computer models can be calibrated with actual response data increasing confidence in the predictive analysis regarding performance of the repaired/strengthened building in future earthquakes

Figure 3. Phases of the post-event assessment response process.

The immediate response phase refers to the onsite response action immediately after the shaking and the "dust settles". The natural inclination of most occupants is to immediately evacuate a building following a major earthquake. Avoiding unnecessary evacuations is critical especially for essential facilities such as hospitals, acute care medical facilities, emergency operations centers, strategic military installations, nuclear power plants, and prisons and detention centers. Occupants of these facilities cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Therefore, the goal with respect to immediate response is more about enabling continued occupancy and operation, and less about triggering an evacuation as is often thought to be the case. The OASIS system alarms and notifications provide confidence to building operation personnel that it is OK to recommend occupants stay inside and continue "business as-usual" or commence emergency response/cleanup operations. It is also important to note that onsite building operation personnel may trigger an evacuation for reasons other than structural damage. Damage to contents or building systems may prevent continued operation of the facility, and so onsite personnel require occupancy evaluation guidance that is broader than just the structural response information from the monitoring systems.

The post-earthquake inspection phase occurs as soon as possible but can be up to a few days to weeks depending on the extent of regional damage and the contractual arrangement between the facility and inspecting engineers. Event information from the OASIS system can be used to aid inspecting engineers in the inspection and tagging process. For example, specific floors that exceeded thresholds can be initially targeted for inspection. More detailed building response data may be provided using post-processing tools and the results presented in a brief report or handout to supplement the immediate information provided by the OASIS system. This quantitative information is an invaluable supplement to the usual post-earthquake inspection process, which is based predominately on visual indicators of damage. This is especially the case in modern buildings with cladding and interior systems that prevent access to the underlying structure. In these cases the level of structural damage must be inferred from damage to non-structural systems, which is dependent on particulars such as the quality of detailing etc., and therefore highly variable. The quantitative data provided by the monitoring system helps inspecting engineers reach less conservative conclusions regarding the acceptability of the subject building for continued occupancy.

Lastly, the detailed evaluation and recovery phase can extend over a period of months. Main event and the inevitable aftershock data can aid in the subsequent engineering evaluation in assessing potential damage, need and priority of any structural system inspections, and extent of required repairs. This is particularly applicable for pre-Northridge steel moment-resisting frames which are susceptible to fracture of the welded beam-column connections in strong ground shaking. This damage was first detected in the 1994 Northridge, California earthquake, and is relatively difficult to detect and expensive to repair. The FEMA-352 (2000) document; *Recommended Postearthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings*, requires inspection of a random percentage of connections for all buildings of this type that experience shaking in excess of a specified threshold level [5]. These guidelines are likely to be adopted by local jurisdictions following a significant earthquake and the data from these systems may be submitted to justify a reduced inspection program where appropriate. The City of San Francisco Department of Building Inspection's Building Occupancy Resumption Program includes the following text in Section D.5 of the required program format: "*Placement of accelerometers. Instrumentation is recommended as part of an Emergency Inspection Program for all highrise buildings in San Francisco. Correct placement of accelerometers can provide valuable post-earthquake information about the performance of a building. This option may be considered in certain cases as a means of reducing the percentage of joints required to be inspected after an earthquake.*"[3]

Regardless of structural system type, having quantitative data on the seismic/structural performance of a building that is to undergo detailed engineering evaluation, or repair/strengthening design, is invaluable to a practicing engineer. Computer models of the building can be calibrated against actual performance increasing the confidence of the predictive analysis regarding performance of the repaired or strengthened building in future earthquakes

3 CASE STUDIES

Case studies from several buildings are presented here.

3.1 CALTRANS District 4 Headquarters and Other Bay Area Buildings

Several buildings in the bay area have been outfitted with structural monitoring systems as part of an enhanced rapid PEA program, see Figure 1. These projects are similar in scope thus only one example; the Caltrans District 4 headquarters, is presented here.

Degenkolb Engineers designed a seismic retrofit scheme for this 15 story steel moment-resisting frame constructed in 1991 and located in Oakland, California, Figure 4. The building is the headquarters for Caltrans District 4 and houses the Transportation Management Center for the San Francisco Bay Area. Previous testing indicated that the welded connections were vulnerable to fracture, and consequently the building presented a risk to life safety in the event of a major earthquake.

After considering several retrofitting schemes, one that included strengthening some existing connections and adding viscous dampers was selected. To meet the seismic performance requirements of the State of California, Department of General Services this scheme reduced interstory drifts to 1.8% in a 475-year return period event. Non-linear time history analyses were performed to verify the performance of the retrofitted structure. Full scale connection testing and detailed finite element analyses were also performed to verify the deformation capacity of the proposed retrofit details. The extra steps taken beyond typical engineering practices were intended to provide better assurance that the project's performance goals would be met during the design basis seismic event.

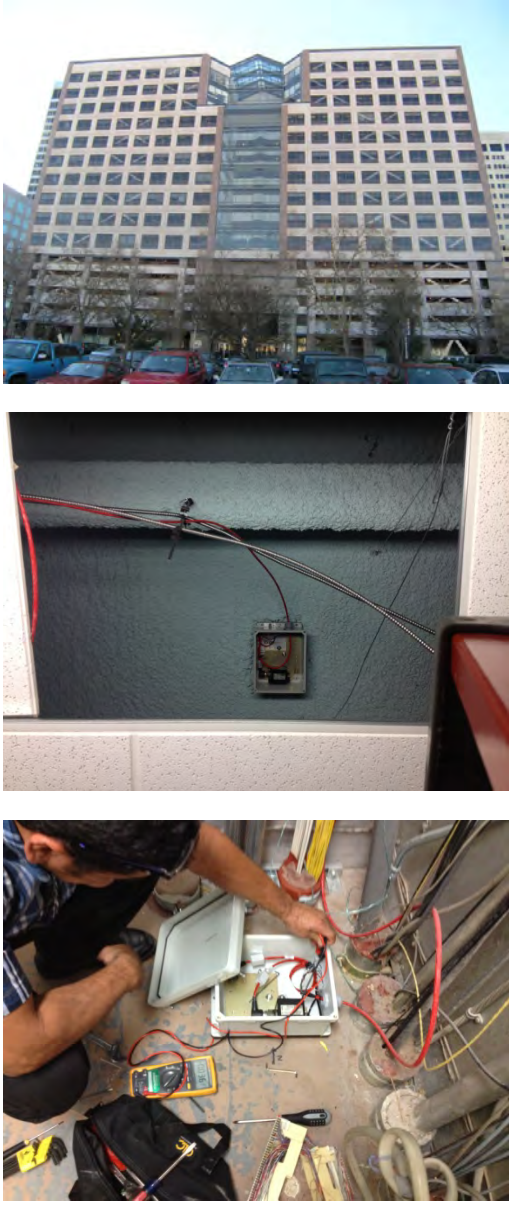


Figure 4. Caltrans District 4 headquarters (top) and example sensor locations.

As part of the project, Caltrans elected to install a 36 channel OASIS monitoring system to enable enhanced rapid PEA. The system is remotely monitored in real-time by Degenkolb Engineers from both the nearby Oakland and Portland offices. This increases the likelihood that event data from the building can be evaluated shortly after an event while inspecting engineers are in transit to the building. As part of the PEA process, Degenkolb Engineers are contracted to monitor the system and perform post-earthquake building inspection. A comprehensive post-earthquake inspection manual was developed which integrates the monitoring system into the overall response process.

Results from analyses performed as part of the retrofit were used to set drift performance limits. The alarms are intended to provide direction on what floors have experienced the highest levels of demand. The overall alarm level for the building will be triggered if three or more drift measurements are above the alarm thresholds described in Table 1

Table 1. Alarm drift thresholds and corresponding actions.

Drift	Description	Action
N/A	Not Triggered	No Action
0.1%	Noticeable building movement	Perform remote evaluation using data from the system
0.5%	Minimum expected threshold for fracture of some unretrofitted pre-Northridge connections	In conjunction with other triggers or communication with building, activate the engineering inspection of the building
2.0%	Minimum expected threshold for damage to the primary lateral system	Evacuation is not triggered automatically but may occur after remote review of data and communication between onsite personnel and inspecting engineers

3.2 US NAVY Hospitals and Medical Centers

As early as 2002, the US Navy developed and deployed building-specific post-earthquake evaluation plans utilizing seismic instrumentation to facilitate rapid and accurate post-earthquake evaluations of several of their essential medical facilities [1]. Since then this program has evolved in to the Rapid Evaluation and Assessment Program (REAP). This program utilizes facility-specific inspection criteria and seismic monitoring systems to provide occupants of these essential facilities post-disaster inspection tools that can be used to perform fast, accurate and detailed building safety evaluations. Combining the principals of Performance-Based Earthquake Engineering (PBEE), known drift limit states of various building materials and structural systems, and the Post-Earthquake Safety Evaluations of Buildings (ATC-20) standard of care, the REAP utilizes a Seismic Monitoring System (SMS) to help facility managers quickly and accurately evaluate the post-disaster safety of these important facilities. This innovative post-disaster safety assessment program has been deployed at the three of the US Navy's west coast-based healthcare facilities: Naval Hospital Bremerton (NHB), Naval Medical Center San Diego (NMCSD), and Naval Hospital Twentynine Palms (NHTP) [4]. NMCSD is the world's largest military medical facility – Figure 5.

As part of their design of seismic upgrades to the 6-story, 1.2 million square-foot NMCSD facility, Reid Middleton developed and deployed the REAP and SMS for this essential facility. The SMS consists of an initial phase of 36 channels of real-time seismic monitoring with a full build out of 60 channels when the program is fully deployed. The Kinemetrics OASIS system was utilized in this project. The REAP makes use of the SMS to measure earthquake performance of the facility and provide real-time feedback to the post-disaster inspection team. REAP inspection tools also include annotated facility drawings, checklists, maps, photography, and related inspection information to allow the safety assessment teams to quickly and accurately examine the structure for post-disaster occupancy. The REAP SMS connects to and deploys building seismic performance data to the USGS Advanced National Seismic System (ANSS) Network. See Figure 6 for the NMCSD SMS Master Plan.

Figure 5. Naval Medical Center San Diego (NMCSD)

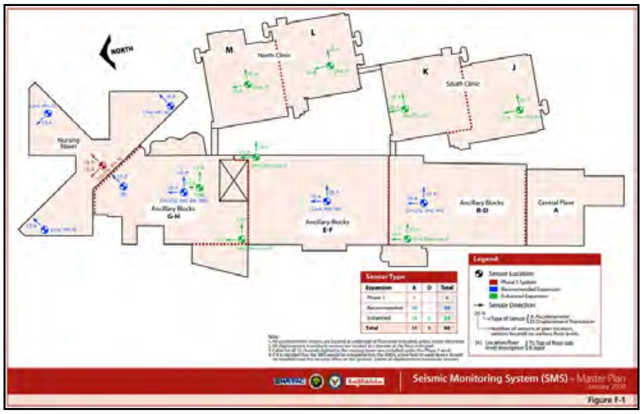


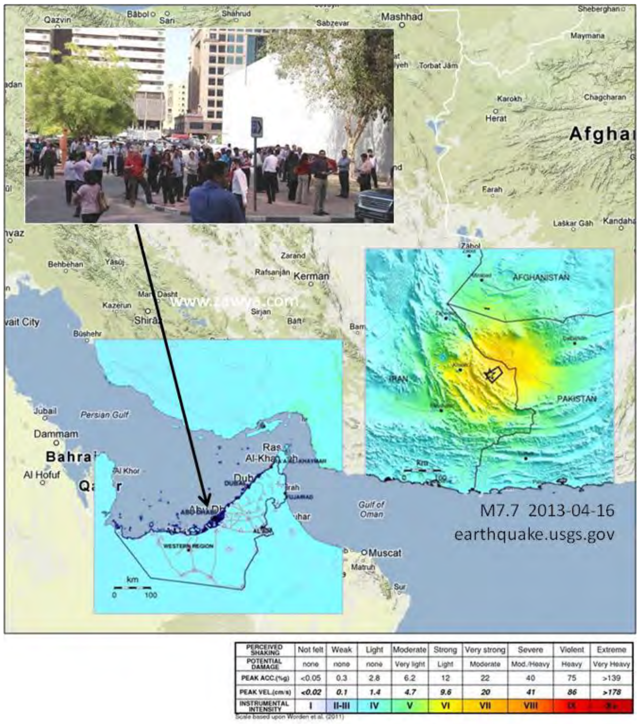
Figure 6. NMCSD SMS Master Plan.

3.3 Abu Dhabi SHM Network

To assure sustainable development of the Emirate of Abu Dhabi, and cultivate a disaster-free living environment for its citizens, the Abu Dhabi Municipality initiated the project "Assessment of Seismic Hazard and Risk in Emirate of Abu Dhabi [7]. The primary objective was to develop a state-of-the-art system to assess, monitor, mitigate, and update the seismic hazard and risk that exists in the Emirate. As part of this large innovative project, one task included the design and implementation of a structural health monitoring network of seven unique and tall buildings distributed throughout the Emirate. Some participating buildings are shown in Figure 7.

Figure 7. Select Abu Dhabi buildings chosen for study and SHM system installation.

In April 2013, two large earthquakes struck the region of southern Iran. ShakeMaps created by USGS [8] and the new Abu Dhabi network for the M7.7 2013-04-16 Sistan-Baluschestan earthquake are shown in Figure 8. Although very far away and producing seemingly very low levels of shaking, both events resulted in mass evacuations across many Gulf countries including Abu Dhabi. One obvious explanation for the understandable widespread reaction is that the region is simply not use to seismic activity. However, there is an additional possible reason that is revealed through careful examination of the data from the instrumented tall buildings.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Figure 8. ShakeMaps and evacuation from M7.7 2013-04-16 Sistan-Baluchestan Earthquake.

The middle plot in Figure 9 displays the acceleration history at the top level of a tall building during the M7.7 2013-04-16 event. The acceleration amplitude is quite low, approx 0.01g, but the shaking does seem to last a long time. To better understand exactly how long the level of shaking persisted above specific levels of human response, the RMS velocity levels in dB are computed for several floors [9]. The thermometer scale on the left hand side of Figure 9 correlates the estimated human response to various RMS velocity levels. For example, the threshold of human perception is approx 65dB whereas the point at which people begin to have difficulty with certain tasks such as reading computer screen is set at 90dB.

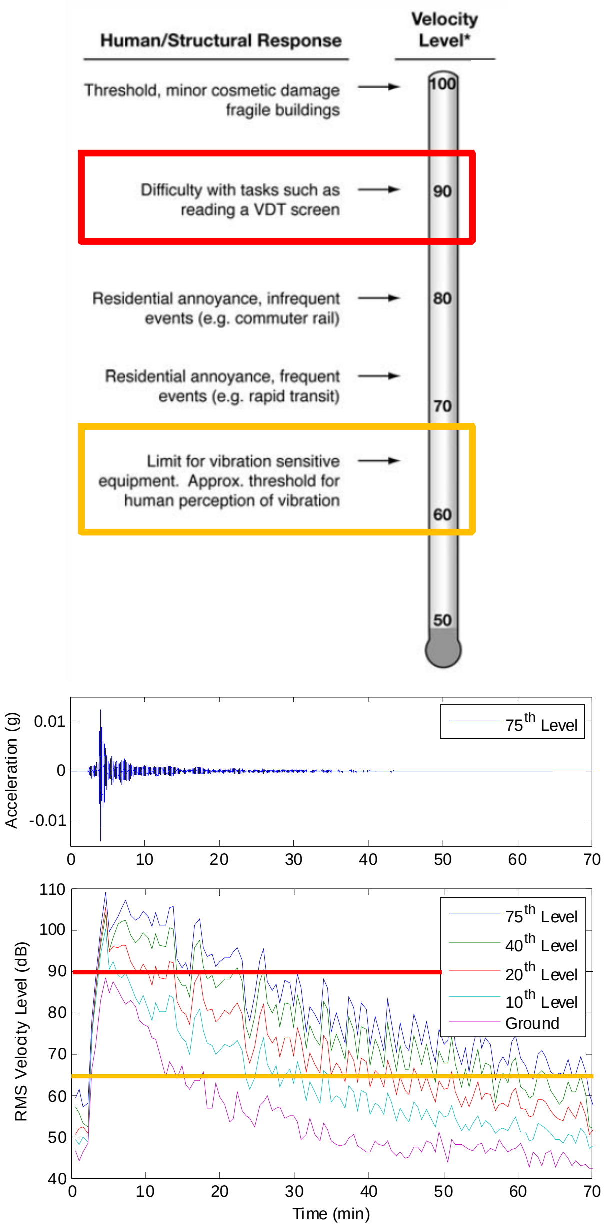


Figure 9. Acceleration and vibration levels recorded at various floors of a tall Abu Dhabi building during M7.7 2013-04-16 earthquake with ground-borne vibration level scale.

From the bottom plot in Figure 9, it can be seen that for floors 20th and higher, the shaking amplitude was above the threshold of task difficulty (90dB) for more than 10mins, and from the 40th floor and higher, the shaking was above the threshold for human perception for almost one hour! Clearly, such long lasting shaking would bring about discomfort in even the most experienced inhabitants of active seismic regions.

4 LESSONS LEARNED AND CONCLUSIONS

Structural monitoring systems, such as Kinemetrics OASIS, provide timely information that can be useful in all phases of post-event response if the information processing is well integrated within the overall PEA plan. Experiences gained through projects such as those presented as case studies here offer invaluable insight into what is required to implement a comprehensive three-phase response plan towards enhanced rapid post-earthquake inspection and assessment. The following is a summary list of observations and lessons learned from this early important work.

1. It is easier to get funding for this type of work if the system is part of a larger retrofit or new design construction project.
2. The engineering implementation work and cost can be significant.
3. Generally, cabling does not present a significant cost compared to the hardware and implementation costs, however; restricted access and the existence of hazardous materials may change this.
4. It is simpler to obtain independent standalone communication (e.g., DSL) for remote access and real-time monitoring than it is to utilize existing infrastructure because building network administrators are usually reluctant to provide support and access though firewalls.
5. While false positives are rare and minimized by careful selection of trigger thresholds and logic, they can still happen, so executing evacuations or other shutdown actions based on automatically generated system output should be avoided.
6. Real-time monitoring is crucial to ensure that the system is always operational and improves the likelihood of the information being available outside the affected region after a large earthquake.
7. Small events are useful to refresh stakeholders' memories and prevent lapses in system maintenance. Data can be used to investigate issues and provide decision making support.
8. Data from significant events can also be used to offer better understanding into responses of occupants (e.g., evacuation for seemingly low level shaking) and provide them useful information. For example, the results illustrated in Figure 9 can be shared with building occupants to help them understand what they just experienced and how it relates to safety.

Ongoing collaborative efforts among leading technology providers and consulting engineers will lead to more lessons learned and continued rewarding results for their customers and the overall earthquake engineering community

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