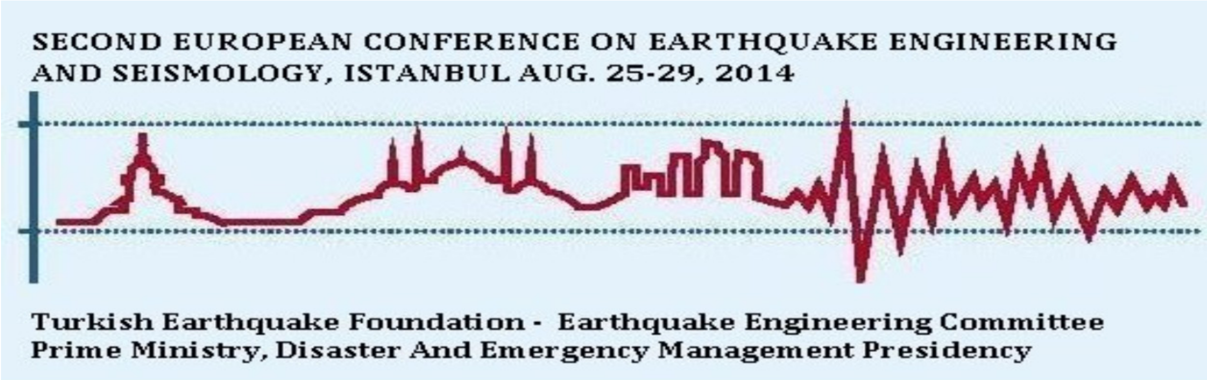

STRUCTURAL HEALTH MONITORING OF UNIQUE STRUCTURES IN ABU DHABI EMIRATE

Derek Skolnik[1], Mauricio Ciudad-Real[2], Mathias Franke[3] Yavuz Kaya[4]and Erdal Safak[5]

ABSTRACT

The term "Structural Health Monitoring (SHM)" refers to the real-time monitoring and alerting of structures state-of-health. The primary objective of SHM is to improve safety and reliability of civil infrastructure by detecting damage before it reaches a critical state and to enable rapid post-event (e.g., earthquake) assessment. In addition, the data from afforded SHM systems are used to validate design assumptions and codes, to predict response for large excitations, to calibrate analytical models, and to develop instantaneous damage and loss maps.

As part of the Emirate of Abu Dhabi Seismic Hazard and Risk Assessment (ADSHRA) project, several unique and prestigious structures in Abu Dhabi were installed with state-of-the-art SHM systems. Typical systems are composed of up to 30 accelerometers within the building, a wind velocity/direction sensor at the roof, and a three-component downhole accelerometer near the building footprint. Data from these systems are all time-synchronized and recorded continuously at 200sps in real-time. A real-time data processing and analysis software package is developed to observe and display the dynamic characteristics (e.g., modal frequencies, damping ratios, and mode shapes) and responses (e.g., accelerations, velocities, displacements, and inter-story drifts) of the structures and their time variations. Since most of the SHM data are due to ambient forces (i.e., low amplitude vibrations with very low signal-to-noise ratios), advanced signal processing and system identification techniques, based on statistical signal processing and stochastic filtering theories, are used for data processing and analysis.

In April 2013, two large earthquakes struck the region of southern Iran. Although very far away and producing seemingly very low levels of shaking, both events resulted in mass evacuations across many cities throughout the 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, analyses of data recorded in several tall Abu Dhabi buildings during these events provides additional unique insight into human perception and structural response to prolonged vibrations of ultra tall buildings due to shaking from large distant earthquakes.

This paper first presents a brief description of the larger ADSHRA project with special detail given to SHM portions. Results and interpretations of data analyzed from recent large but distant earthquakes are then presented.

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INTRODUCTION

To assure sustainable development of the Emirate of Abu Dhabi in the United Arab Emirates, and cultivate a disaster-free living environment for its citizens, the Abu Dhabi Municipality initiated the project “Emirate of Abu Dhabi Assessment of Seismic Hazard and Risk” or ADSHRA, Milutinovic and Almulla (2013). The primary objective of the project is to assess, monitor, mitigate and update the seismic hazard and risk that exists for the Emirate of Abu Dhabi. This is achieved via a multifaceted approach involving not only ground observations and geologic studies, but also Structural Health Monitoring (SHM) systems in representative and unique tall buildings, and culminating in real-time seismic monitoring and emergency management data and display centers, Fig.1. Brief descriptions of select project tasks, which are listed in Table.1, are highlight here.

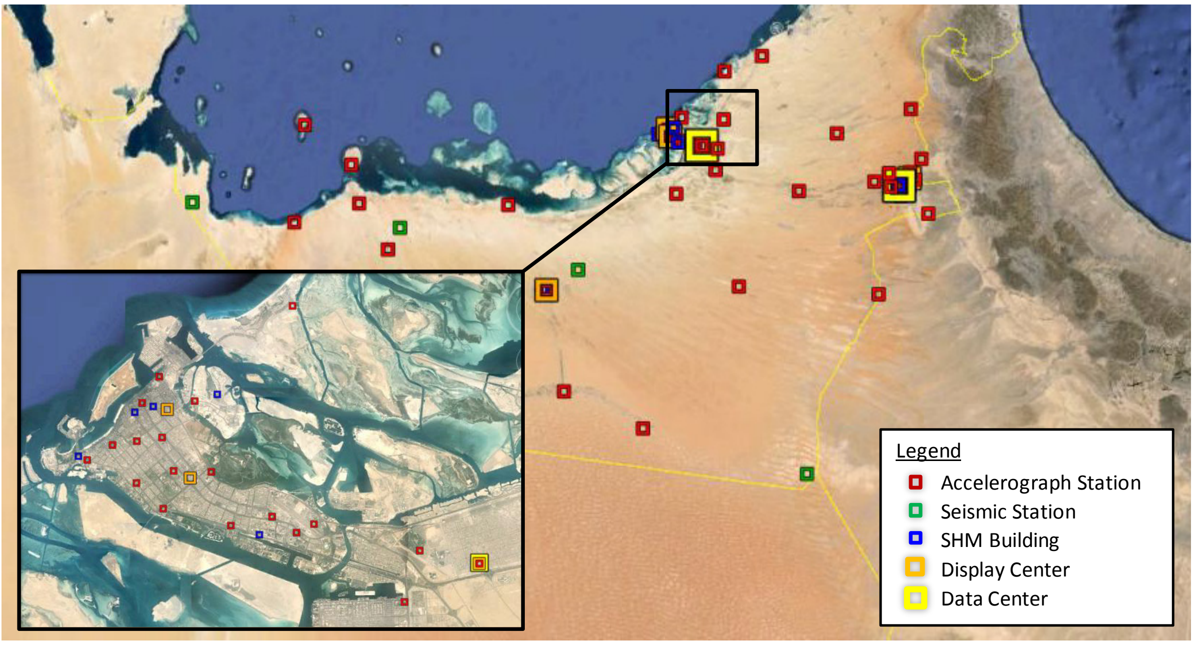

Figure 1. Network of strong-motion stations (50), broad-band seismic stations (4), structural health monitoring systems (7), disaggregate mirrored data centers (2), and display centers (5) installed under ADSHRA project

Seismic Hazard, Microzonation, and Risk Assessment

The seismic risk assessment examined the seismic vulnerability, performance, and risk of critical structures and lifelines (electric power, water supply, gas transportation, and oil transportation systems, etc.), and identified the risk level inherent to current design and construction practices within the Emirate of Abu Dhabi. Site amplification, liquefaction susceptibility, and microzonation studies were conducted to estimate the influence of local soil conditions upon the amplitude and frequency content of regional seismic events.

A seismic source model for the UAE region was developed based on the tectonics, seismicity and topographic features of the region, which is comprised of three areal active shallow regions; a linear source zone, a subduction zone, and a background zone, with recurrence intervals determined from historical and instrumental seismicity. Ground motion prediction equations were developed based on three distinct tectonics regimes surrounding the UAE: a stable continental region, an active shallow region, and a subduction zone. Probabilistic and deterministic seismic hazard assessments were conducted to define and map design ground motion parameters, including peak ground acceleration, velocity, modified Mercalli intensity, and 5% damped spectral accelerations for both long and short periods; as well as for tall buildings to establish performance levels, including serviceability limit state (immediate occupancy), damage control limit state (life safety), survival limit state (collapse prevention), and maximum credible hazard scenario. All parameters calculated were provided to the client in map form (i.e. GIS), with the spatial distribution of the design parameters presented at both the UAE regional level and a finer level for microzonation studies.

Table 1. ADSHRA Task Descriptions and Objectives

Task	Description	Objective
01	Seismic Hazard Assessment and Zoning	Probabilistic and deterministic seismic hazard assessment for development of performance-based building design code
02	Site Amplification and Microzonation Studies	Estimation of the influence of local soil conditions upon amplitude and frequency content of regional seismic motions
03	Liquefaction Susceptibility Study	Analysis and estimation of liquefaction susceptibility at sites composed of, or prevailed by, “potentially liquefiable” soils
04	Seismic Design Parameters Web	Development of a webpage providing seismic (and wind) design parameters in format complying with 2006 IBC
05	Seismic Risk Analysis of Critical Lifeline Systems	Assessment of the seismic vulnerability, performance and risk of selected critical infrastructure and lifeline systems
06	Seismic Risk Analysis of Critical Structures	Identification of the risk level inherent to current building design and construction practice under pertinent seismic hazard conditions
07	Strong Motion Accelerograph Network	Furnish and install 50-station strong-motion network including disposition of potential station locations
08	Seismic Monitoring Network	Furnish and install 4-station seismic monitoring network including disposition and site study of potential station locations
09	Ground Shaking Map	Develop and implement ground shaking map (i.e. USGS ShakeMap) for Abu Dhabi
10	Structural Health Monitoring Systems	Furnish and install complete structural health monitoring systems for 7 unique and representative buildings
11	3D Seismic Simulation Model for Long-Period	Construction of 3D numerical seismic velocity model for predicting long period (0-1 Hz) earthquake strong motion waveforms
12	Seismic Risk Analysis of Tall Buildings	Identification of the risk level inherent to tall buildings to long period ground motions generated by 3D seismic simulation model
13	Seismic Risk and Loss Estimation	Development of urban vulnerability model, definition of building typology matrix, development of fragility curves, and estimation of population dynamics for assessing seismic risk and loss potential
14	Monitoring and Management Centers	Establish two disaggregated mirrored data centers and five display centers for data acquisition, processing, storage, maintenance, display and emergency dissemination of results and information
15	Seismic Database and GIS Shell	Development of suitable seismic database with management software, hardware, data model with GIS visualization of results
16	Coordinated Activities	To assure coordination of project works with complementary activities undertaken under other ongoing projects and transfer of achievements required
17	Promotion & Public Awareness	Promotion, international validation of achievements of the Project "Assessment of Seismic Hazard and Risk in Emirate of Abu Dhabi" by organizing thematic Workshops and other professional gatherings with national and international participation
18	Training	Skill enhancement of the identified Department(s) and their Consultant staff in operating and maintaining the function of the system and use it for scenario seismic hazard, risk and loss analyses
19	Build, Operate, Transfer	Post-implementation period for smooth transfer of knowledge and ownership
20	Maintenance	Five years maintenance agreement

Site Studies

A full suite of geotechnical measurements (micro-tremor, seismic refraction, liquefaction analysis, borehole drilling and analysis, etc.) was conducted at each station location, as well as, near buildings equipped with SHM Systems, to assess site suitability. These assessments were then archived, and used to calibrate and refine data for the GIS system designed to work with the real-time seismic monitoring and management center described in subsequent sections.

Strong-Motion, Seismic, and SHM Networks

The strong-motion network comprises of fifty accelerograph stations. Kinemetrics Shallow Borehole EpiSensors are installed at 35 free-field sites, and at an additional 5 sites accelerograph arrays are installed at both 3- and 30-meter depths. Completing the network are 10 surface EpiSensors installed in open ground sites or small buildings; Fig.2 displays the different strong-motion station types. All stations are equipped with Kinemetrics Basalt Digitizers with GPS antennas, Sierra Wireless Raven XE 3G modems and solar panels, Fig.2. The stations are distributed with the intent of providing the maximum reliable coverage of the emirate and to provide robust data for the seismic monitoring center, with an emphasis on existing urban areas and areas currently under development, Fig.1. The acquired data will be used to develop and implement ShakeMap, establish parameters for structural design, verification, and calibration of current seismic codes, as well as provide detailed lithostratigraphic and geotechnical site characteristics.

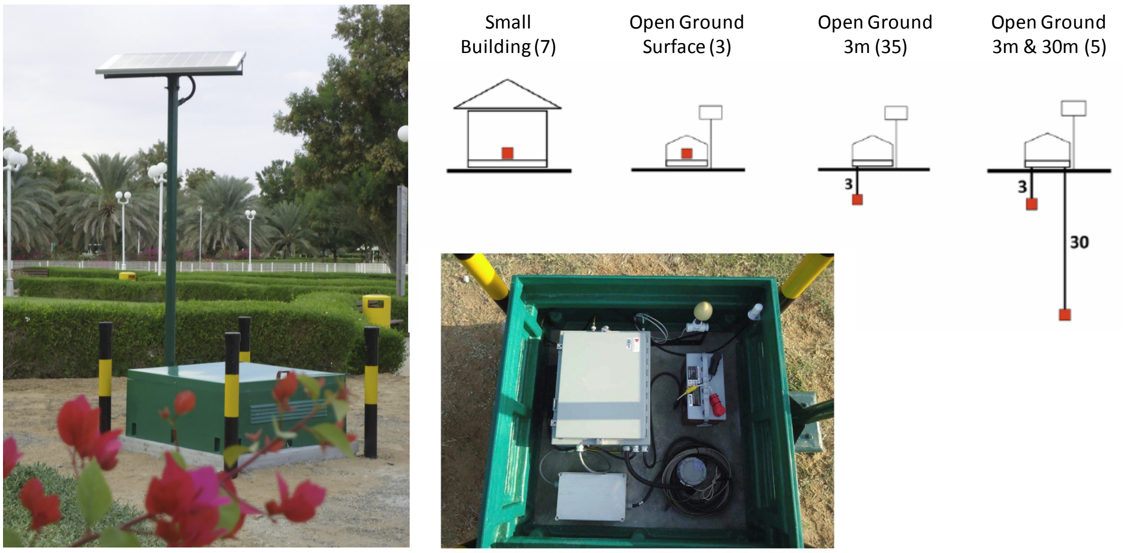

Figure 2. Types (and quantities) of strong-motion accelerograph stations installed under ADSHRA project with example photo of open ground type with 3m borehole.

The seismic network consists of four broadband seismic stations installed to enhance the existing Emirate of Abu Dhabi seismic monitoring network. Each station contains a broadband seismometer (CMG3T) and accelerometer (EpiSensor) in order to record both velocity and acceleration data in real-time, Quanterra Q330 digitizers, and VSAT telemetry. The primary function of the broadband stations is to improve the quality of existing data for the construction of a 3D seismic simulation model for the simulation of long period seismic waves leading to better understanding of the crust and crustal fracturing processes in the region.

Several unique and representative structures were selected for seismic performance and other studies, and seven were instrumented with state-of-the-art SHM Systems, Fig.3, designed to provide real-time critical information, status alerting, rapid post-event assessment, and to improve overall safety and reliability, Fig.4, Skolnik and Ciudad-Real (2013). Potentially damaging conditions, such as extreme response and fatigue, can be detected quickly after an event (e.g., an earthquake or strong windstorm). The SHM Systems are comprised of up to 30 acceleration sensors within the building, an ultrasonic wind speed/direction sensor (WindObserverII) at the roof, and a three-component downhole acceleration sensor near the building footprint. Data from these systems are all time-synchronized and recorded continuously at 200sps in real-time using Kinemetrics 24/36 channel Dolomite central recording systems. For real-time onsite system monitoring, display, and alerting, an industrial rack-mounted panel-PC with an alarm panel and UPS is installed at each selected building. A real-time data processing and analysis software package (REC_MIDS) is developed to observe and display the dynamic characteristics (e.g., modal frequencies, damping ratios, and mode shapes) and responses (e.g., accelerations, velocities, displacements, and inter-story drifts) of the structures and their time variations. Since most of the SHM data are due to ambient forces (i.e., low amplitude vibrations with very low signal-to-noise ratios), advanced signal processing and system identification techniques, based on statistical signal processing and stochastic filtering theories, are used for data processing and analysis.

Figure 3. Some of the buildings selected for SHM, seismic performance and other studies.

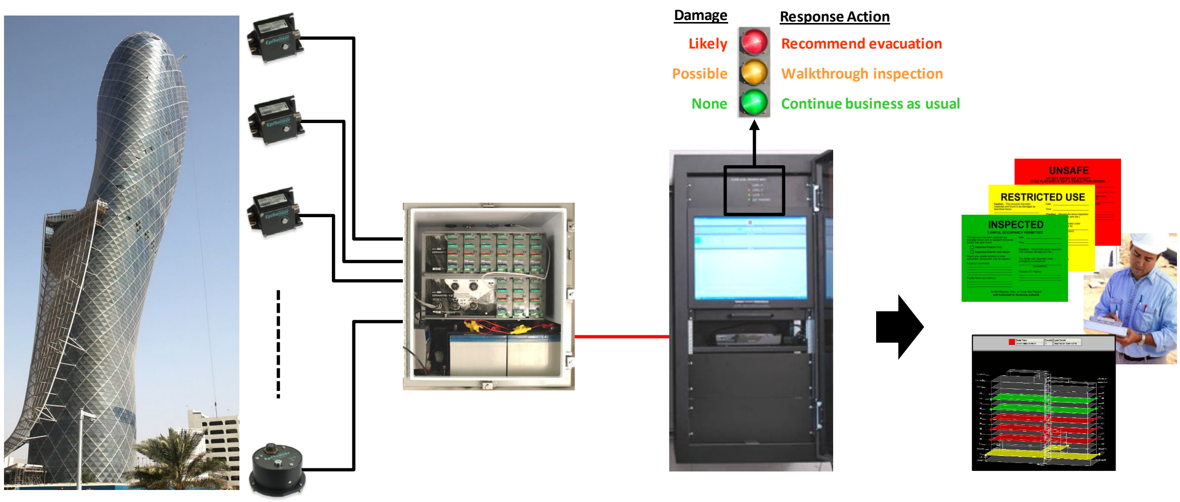

Figure 4. SHM system consisting of Kinemetrics OASIS monitoring solution and REC_MIDS software.

Seismic Risk Monitoring & Management Center

The Seismic Risk Monitoring and Management Center (SRMMC) is a disaggregated system comprised of two mirrored data centers and five display centers. The data centers receive real-time data from the accelerograph, seismic, and SHM networks. Data from existing seismic networks of the National Center of Meteorology and Seismology in Abu Dhabi (NCMS), Dubai Municipality, Oman, and Kuwait are also integrated into the system. All data, acquired through the seismic hazard, microzonation, and risk assessment studies, as well as the newly acquired data received from the accelerograph and the seismic monitoring networks, are compiled into a GIS database that will be used for rapid calculation and display of seismic and loss estimation for emergency management personnel. The GIS database and application servers are also located in the data centers.

Kinemetrics' ASPEN Open System Solution is used to provide a comprehensive and integrated platform, with both on-site archival and telemetered data streams. BRTT's Antelope software provides the framework with which to collect, process, and archive the critical real-time data in a robust and reliable manner. The customizable ASPEN System includes extensive network state-of-health monitoring and provides automated earthquake detections and locations in near real-time.

Also developed is an integrated software suite that combines the USGS-written ShakeMap program, Wald and Worden (2005) within the ASPEN real-time system, in order to automatically produce ground-shaking maps almost immediately following a notable earthquake in or around the UAE. When an earthquake is detected and located by the UAE seismic networks, the software suite immediately attempts to download any data that is missing or not triggered from the accelerograph network, then archives the data into the real-time system and produces the ground shaking products. ShakeMaps are generated for every origin located by the real-time system, and the computed grid files are uploaded to a FTP server for GIS refinement (for life line and potential building damage estimates), and resulting web pages are published to a web server, accessible to users on the network.

The five display centers are optimally located in each of the three Municipalities of the Emirate of Abu Dhabi (Abu Dhabi, Al Ain, and the Western Region), in the Abu Dhabi Police Headquarters, and at the NCMS main office, Fig.1. The display centers are equipped with semi-interactive video walls, Fig.5, which display relevant system data allowing operators to quickly visualize data flow, seismic station state-of-health, SHM status, any notable earthquakes (as located by the automated system) and associated waveforms, and the ShakeMap and GIS web based products. Operator selectable video feeds at the display centers, together with the GIS and ShakeMap web-services provide a comprehensive picture of the state of emergency in the event of a large earthquake.

Figure 5. Overview of ADSHRA communication layout (left) and photos of display centers.

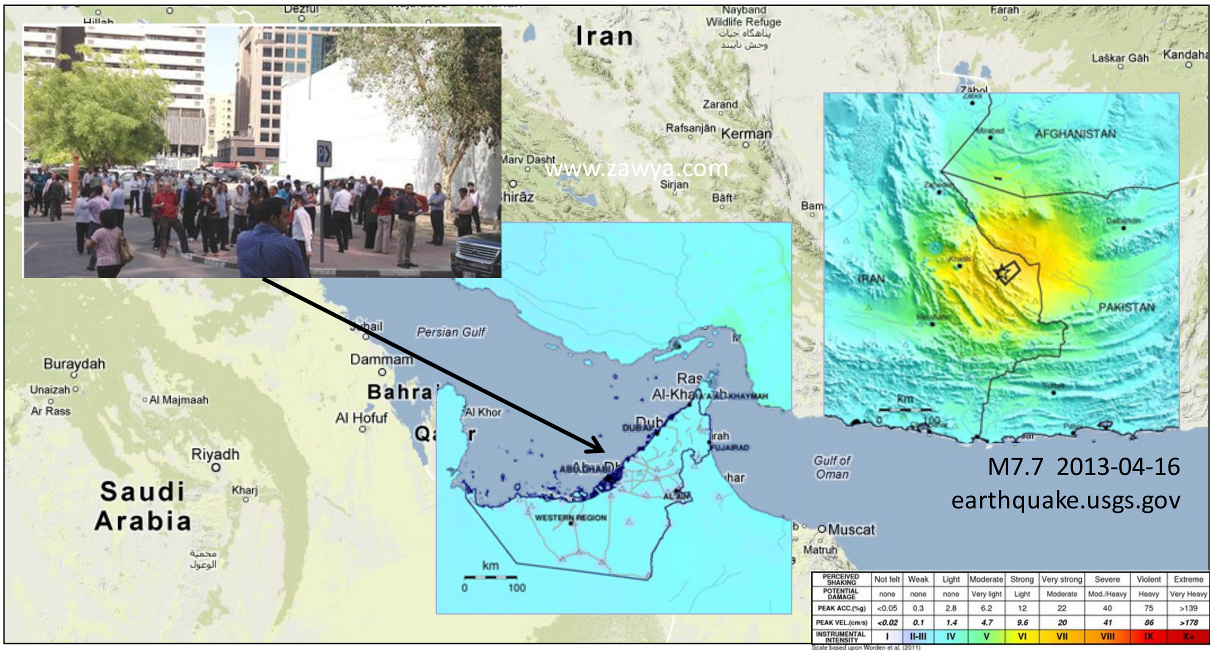

Figure 6. ShakeMaps and evacuation resulting from M.7.7 2013-04-16 Sistan-Baluchestan Earthquake.

APRIL 2013 IRAN EARTHQUAKES

In April 2013, two large earthquakes struck the region of southern Iran. ShakeMaps created by USGS (2013) and the newly installed Abu Dhabi network for the M7.7 2013-04-16 Sistan-Baluschestan earthquake which was more than 800 km away are shown in Fig.6. Although very far away, both events resulted in mass evacuations across many cities throughout the Gulf countries including Abu Dhabi, Fig.6. One obvious explanation for the understandable widespread reaction is that the population 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.

One such tall building instrumented with an SHM system in Abu Dhabi is a ~300m, 70+ story mixed use (office and residential) building situated on a reclaimed island, Fig.7. The structural system consists of reinforced concrete frame and shear walls with a mid-height two-level steel outrigger belt truss system. The floor plan is elliptical as shown in Fig.7, having long/short dimensions of 80m and 33m respectively. More details on the structure and instrumentation layout are available in Skolnik (2012). A detailed analysis of data recorded for the aforementioned event can also be found at Safak (2013). Presented here are some additional results and findings of interest.

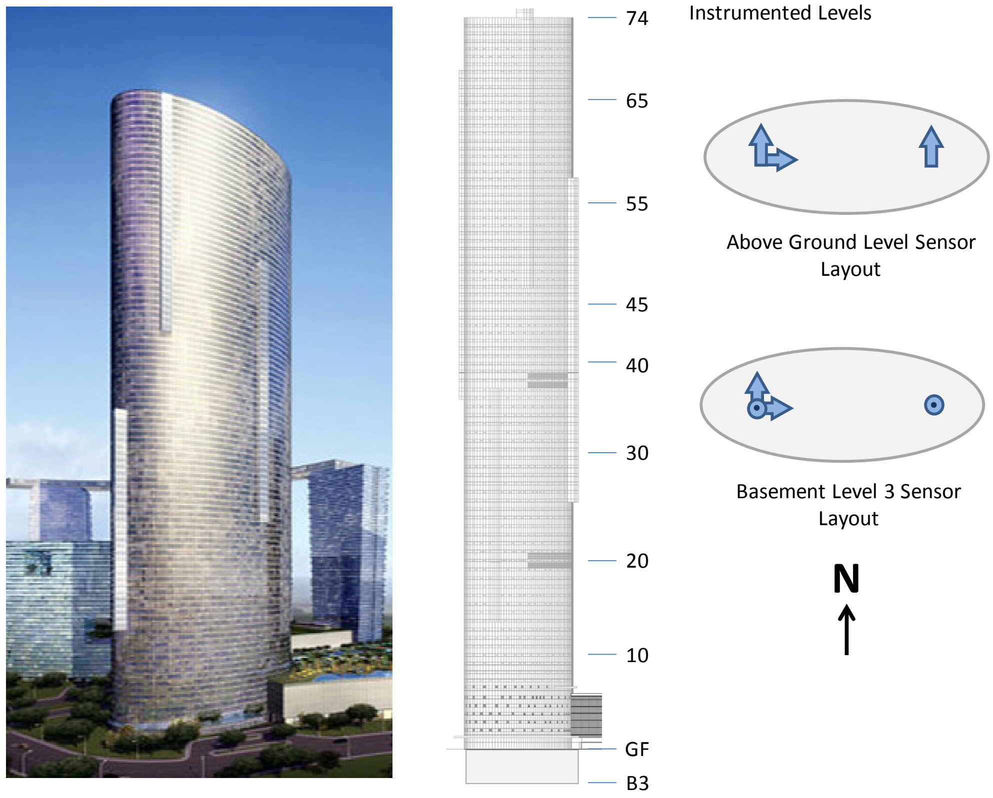

Figure 7. Tall building instrumentation layout.

A strong-motion station of open-ground type with 3m and 30m deep borehole sensors is installed on the same reclaimed island approximately 1.3km away from this tall building. Response spectra at 3% damping of all three components for both 3m and 30m depths are shown in Fig.8. Although most of the energy is in the short-period range, with dominant periods in North-South (NS) at 0.2s and East-West (EW) at 0.35s, there is still relatively considerable energy in the long-period range (>1s). Displacement spectra illustrates the long-period energy even more, see Safak (2013). Fig.8 also displays the spectral amplification (right side) in which an amplification of 2.5 to 3.5 times is observed just below the dominant periods, as well as an amplification of 1.35 to 1.5 for PGA values. These results compare well with the site-specific response analysis based on boring reports and in-situ testing (PS logging and shallow seismic refraction) that were performed as part of the ADSHRA project, Ansal and Kurtulus (2012).

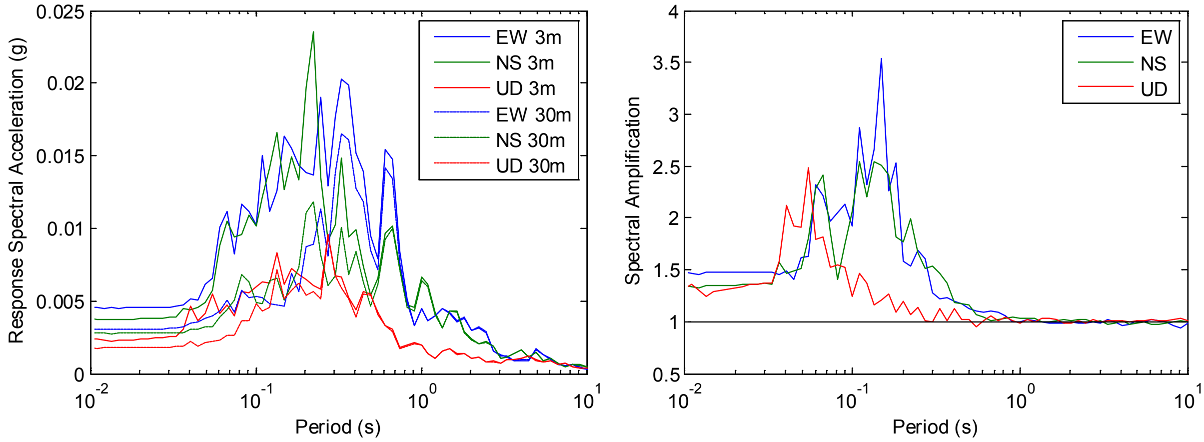

Figure 8. Response spectra from records obtained from nearby open ground strong-motion station with borehole sensor at 3m and 30m depths (left) and spectral amplification (right).

Fig.9 shows the absolute accelerations in the EW (top) and NS (bottom) directions directly measured by the SHM systems whereas Fig.10 shows the EW (top), NS (middle) and torsional (bottom) relative displacements computed at the center of stiffness at each instrumented floor by assuming rigid diaphragms and subtracting out the basement level motions. These figures clearly illustrate the effects of shaking in tall buildings due to long-period surface waves from distant events. Although low in amplitude, the duration of shaking is significant – note the time scales. Fig.9 also clearly shows significant torsional responses, most likely due to the elliptical shape and large cross-sectional aspect ratio.

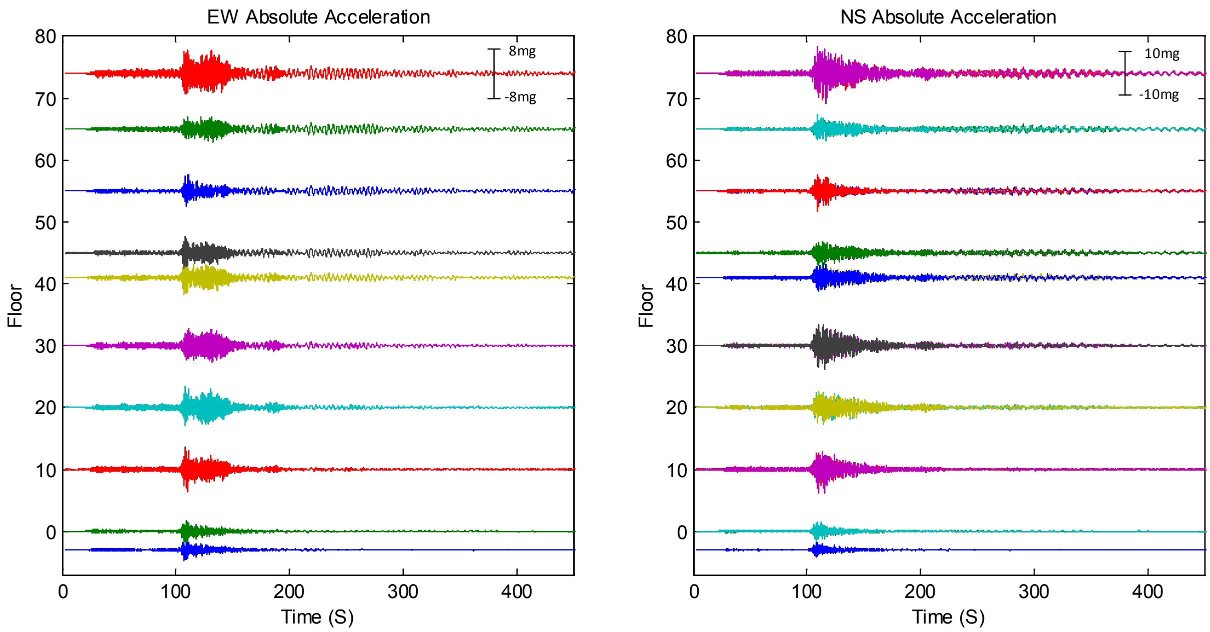

Figure 9. Absolute accelerations measured in Abu Dhabi tall building in east-west (top) and north-south (bottom) directions

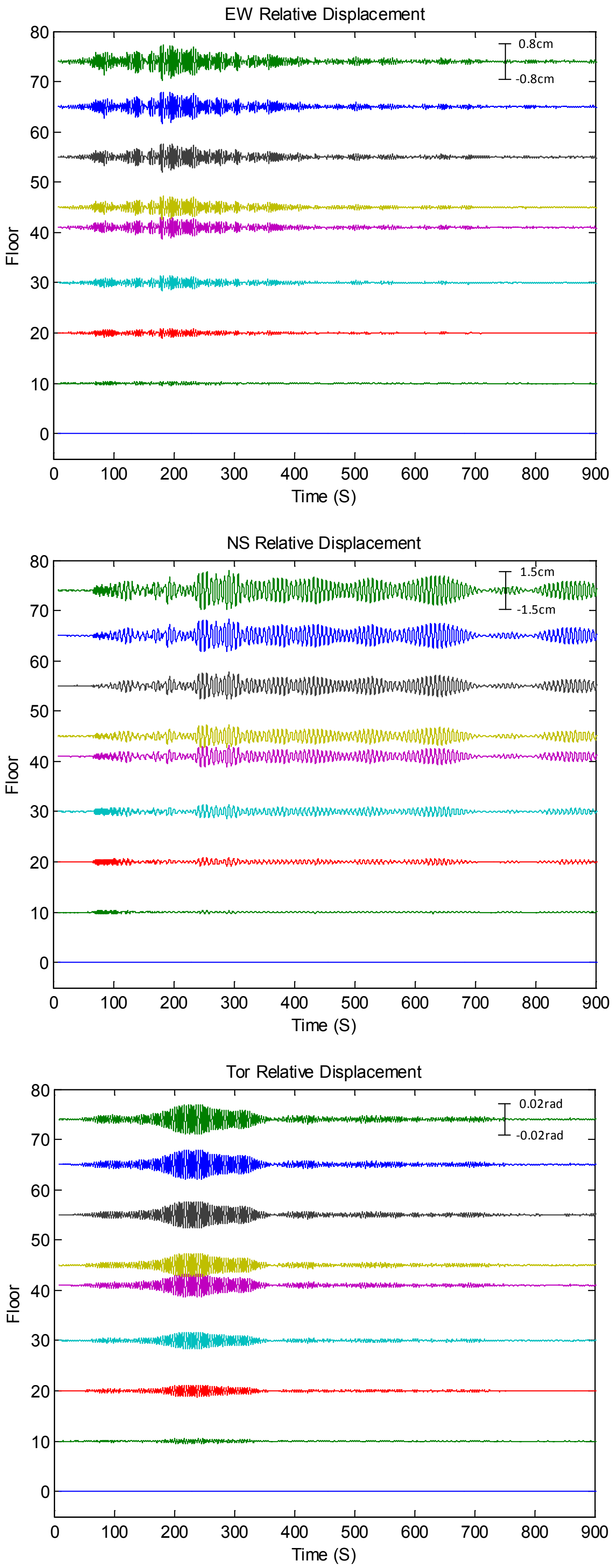

Fig.10 Relative displacements in Abu Dhabi tall building in east-west (top), north-south (middle), and torsional (bottom) directions

Fig.11 shows the Fast Fourier Transform (FFT) of the relative accelerations computed at the floor slab center of stiffness. Using relative acceleration story motions allow us to more readily identify the torsional and coupled modes which are listed Table.2. The modal identification results compare well with the ambient vibration study that was performed prior to instrumentation under the ADSHRA project described earlier, Salic and Safak (2012). From that same study, the overall building damping was estimated in the range of 1.0 to 3.75% of critical, which was used in computation of response spectra in Fig.8.

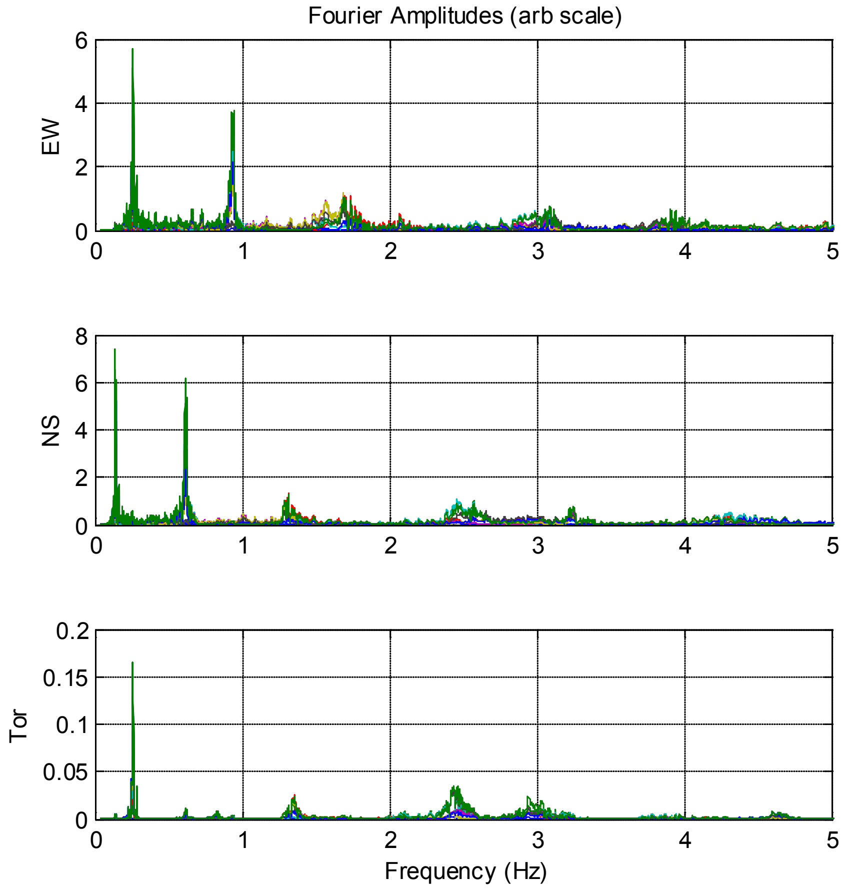

Figure 11. FFT of relative translational and torsional accelerations computed at center of stiffness of floor slabs

Table 2. Identified Modes from April 2013 earthquake and ambient vibration study

Mode	2013 Earthquake Data			2012 Ambient Vibration Test	
	Orientation	Frequency (Hz)	Period (s)	Orientation	Period (s)
1	NS	0.137	7.30	NS	8.0
2	Tor/EW	0.26	3.85	EW/NS	3.56 to 4.0
3	NS	0.62	1.61	NS	1.60
4	EW	0.93	1.08	NS/EW	1.03 to 1.2
5	NS/Tor	1.3 to 1.4	0.71 to 0.77	NS	0.74
6	EW	1.7	0.59	EW	0.56
7	Tor/NS	2.4 to 2.5	0.4 to 0.42	EW/NS	0.32 to 0.39

To better understand exactly how long the level of shaking persisted above specific levels of human perception, the RMS velocity levels in dB relative 10^{-6}in/s are computed for several floors. The thermometer scale on the left hand side of Fig.12 correlates the estimated human response to various RMS velocity levels, Hanson and Towers (2006). 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. From the right plot in Fig.12, 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.

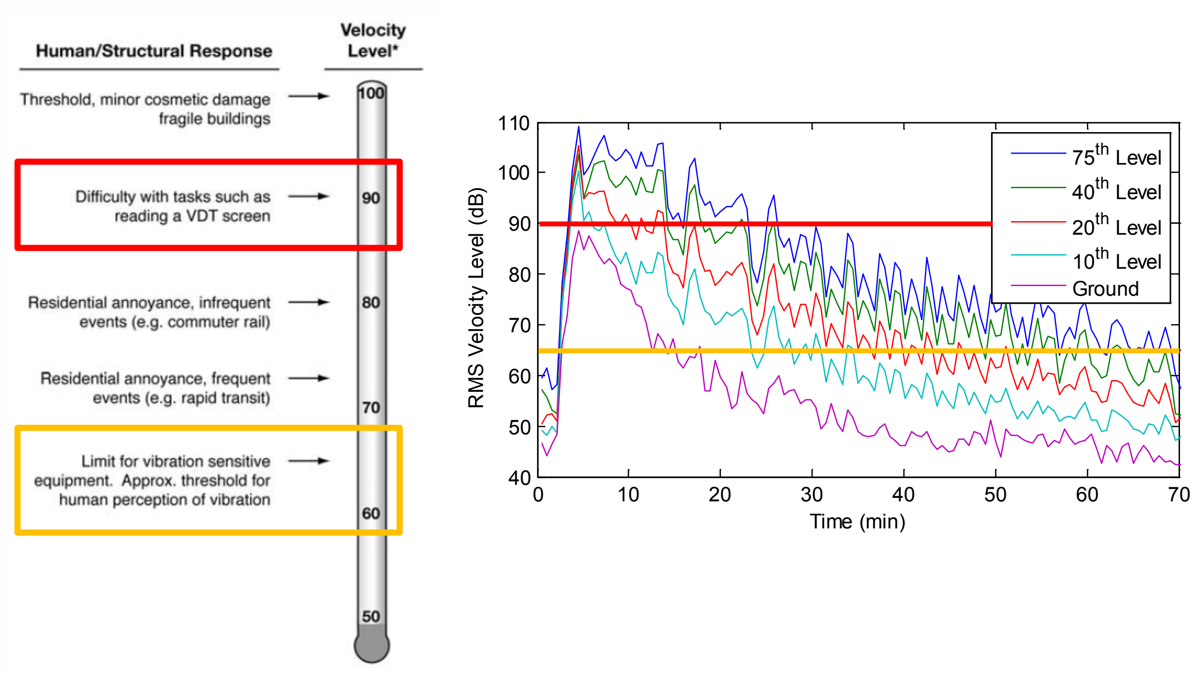

Figure 12. Vibration levels with ground-borne vibration level scale

CONCLUSIONS

Structural monitoring systems provide timely information that can be useful in rapid post-event response and better understanding of the structural behavior to earthquakes. Distant large earthquakes can create long-period long-duration shaking in regions that are not necessarily seismically active. Although low in amplitude, this type of shaking leading to panicked crowds and potential for low-cycle fatigue, particularly in tall buildings.

SHM 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 Fig.12 can be shared with building occupants to help them understand what they just experienced and how it relates to safety.

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