SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

STRUCTURAL HEALTH MONITORING SYSTEMS: STATE-OF-THE ART INFRASTRUCTURE FOR EMERGENCY DECISIONS AND MANAGEMENT OF EARTHQUAKE DISTRESS

Zoran Milutinovic[1], Radmila Salic[2], Ali Megahed[3] and Hassan Almulla[4]

ABSTRACT

On April 9 and 16, 2013, two strong earthquakes affected the territory of UAE. The M6.3 Bushehr (April 9, 2013) and the M7.8 Sistan-Baluchestan (April 16, 2013) Earthquake occurring in Iran, at distances ~500 km and ~850 km from Abu Dhabi, caused significant human distress and panic in Gulf countries. Unpleasant swaying of mid-, and high-rise, and tall buildings leaded to uncontrolled flee of their panicked inhabitants as well as evacuations ordered by building securities.

Such behaviour of high-rise buildings' population is typical and shall be expected when tall buildings are exposed to major distant earthquakes. The emergency systems shall foresee such situations, formalize it and incorporate in their operation plans and procedures.

The paper conceptualises the procedure of estimating the potential of creation of earthquake related human distress situations based on near real-time processing of recordings from structural health monitoring systems in Abu Dhabi, UAE, as well as quantifies elements to be used in emergency decision making process.

1. INTRODUCTION

On April 9 and 16, 2013, two strong earthquakes (Table 1) affected the territory of UAE. The first one, the Bushehr Earthquake (M6.3) occurred on April 9, 2013 (11:52:30.7 UTM), North-Eastern from Abu Dhabi at distance ~500 km, while the second one, the Sistan-Baluchestan (M7.8) Earthquake occurred on April 16, 2013 (10:44:20.9 UTC) North-western from Abu Dhabi at distance ~850 km. Both earthquakes caused significant human distress and panic in Gulf countries, leading to mass flee of inhabitants from mid-, high-rise and tall buildings and demanded massive evacuations of high-rise and tall buildings.

In a similar manner the citizens of Skopje reacted during the Vranchea, March 4, 1977 M7.2 Earthquake occurring at 19:21:54 UTM (20:21:54 Skopje time) at ~600 km from the City. Due to swaying, the high-rises (10-16 storeys) were immediately drained and most of their inhabitants stayed overnight with relatives in low-rise houses or slept in cars.

Such behaviour of high-rise buildings' population in general (Gulf States), and of the population having the 'historic earthquake memory' (Skopje) in particular, is typical and shall be expected when tall buildings are exposed to major distant earthquakes. The emergency systems shall foresee such situations, formalize it and incorporate in their operation plans and procedures, and be

[1] Prof D-r, Department Head, UKIM-IZIIS, Skopje, Republic of Macedonia, zoran@pluto.iziis.ukim.edu.mk
[2] Assist. M.Sc., UKIM-IZIIS, Skopje, Republic of Macedonia, r_salic@pluto.iziis.ukim.edu.mk
[3] D-r, Seismology Expert, Municipality of Abu Dhabi City, Abu Dhabi, UAE, ali.megahed@adm.abudhabi.ae
[4] Eng., Department Head, Municipality of Abu Dhabi City, Abu Dhabi, UAE, Hassan.Almulla@adm.abudhabi.ae

prepared to efficiently amortize impact by adequate action. This is particularly true for seismically safe structural environments when exposed to such earthquakes.

2. PERCEIVED INTENSITY (PI)

The Cyber Platform of the Abu Dhabi Seismic Risk Monitoring and Management Centre (AD-SRMMC) in near real-time generated Ground Shaking Maps (GSM) for both events (Fig. 1). Over the UAE, the computed instrumental intensities, in the following the GSM Intensities (Wald, 1999; Worden at al., 2011) were in ranges 1.0 – 2.7 and 1.4 – 3.5 for the Bushehr (M6.3) and the Sistan-Baluchestan (M7.8), Earthquakes respectively. Within the territory of continental Abu Dhabi Emirate, and the Dubai Emirate GSM Intensities ranged from 1.0-1.7 (Bushehr) to 1.4 – 2.7 (Sistan-Baluchestan) degrees.

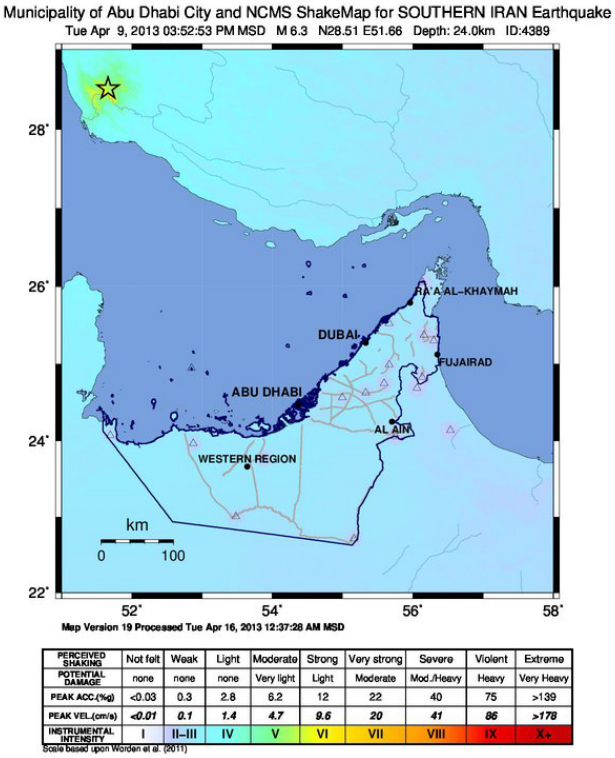
Table 1. General Information on 2013 Bushehr and Sistan-Baluchestan Earthquakes

2013 Bushehr, M6.3 Earthquake	**2013 Sistan-Baluchestan, M7.8 Earthquake**
The M6.3 earthquake of April 9th, 2013 occurred at 11:52 UTC (15:52 Abu Dhabi time) in the region of Kaki, 90 km south-east of Bandar Bushehr, southern Iran. In 48 hours following the main shock, 91 M3.5+ aftershocks have been recorded. Among them, 5 with a magnitude greater than 5 and 42 greater than 4. Reports on felt tremors come from Saudi Arabia, Qatar, Bahrain, Kuwait and UAE (200-700 km from the epicenter), stating that office workers and residents escaped from buildings as fillings the shook. Tremors lasted for around 20 seconds.	A major M7.8 earthquake struck far east Iran near the border with Pakistan, 85 km east of Khāsh, Iran on April 16th, 2013 at 10:44 UTC (14:44 Abu Dhabi time). The earthquake occurred in a sparsely populated area at a depth of 87 km. There were reports of tremors felt in Qatar, Bahrain, Kuwait, Abu Dhabi, in the Gulf, in Afghanistan, in Pakistan and India. In Delhi, more than 1,500 km from the epicenter, office workers evacuated buildings as filling the shook and windows rattled. Tremors lasted for around 30 seconds.

Contrary to the calculated intensities GSM I < 2 (equivalent to MMI II: A few people might notice movement if they are at rest and/or on the upper floors of tall buildings, Table 2) the UAE population reaction to both earthquakes was overwhelming, partially due to inexperience in distant earthquake effects, but dominantly due to the unpleasant swaying of high-rises and tall buildings (Figures 2).

While the GSM intensities in Abu Dhabi and Dubai generated by M6.3 Bushehr earthquake were in range Imm = 1.0 – 1.7 (Figure 1). The testimonies (Annex A) posted on social media indicated that intensities perceived by inhabitants of tall buildings (perceived intensity, PI) were at least twice higher than the calculated GSM intensities.

That was the primary reason why the Abu Dhabi residents, as well as building security services, contacted immediately the Abu Dhabi Police authorities inquiring for caused damages and losses and on building reoccupation safety.



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)	<0.03	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.01*	*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 1. GSM Intensities (Imm) Calculated for M6.3 Bushehr Earthquake of 9 April 2013

"After the tremors, the Abu Dhabi Police have been receiving a flood of calls from residents about the sudden phenomenon.The police assured the residents that there were no casualties or any damage to

properties in the emirate caused by the earthquake. "The Central Operation Room at Abu Dhabi Police has been receiving a number of calls from residents to know if there were any casualties or damages caused by the earthquake in Iran. We assure that there is no casualty or damage in the Emirate," said a spokesman of the police." [Khaleej Times].

Table 2. Excerpt from Modified Mercalli Seismic Intensity Scale (MMI)

MMI Degree	Tremor	Description
I	instrumental	People do not feel any Earth movement.
II	lightest	A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.
III	light	Many people indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.
IV	mediocre	Most people indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement. Parked cars rock.
V	strongly	Almost everyone feels movement. Sleeping people are awakened. Doors swing open or close. Dishes are broken. Pictures on the wall move. Small objects move or are turned over. Trees might shake. Liquids might spill out of open containers.
VI	much fort	Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. No structural damage.

a) Dubai, UAE, Bushehr Eq. of 9.04.2013

c) Dubai, UAE, Sistan-Baluchestan Eq. of 16.04.2013

b) Khobar, Saudi Arabia, Bushehr Eq. of 9.04.2013

d) Abu Dhabi, UAE, Sistan-Baluchestan Eq. of 16.04.2013

Figure 2. Population Reaction to Bushehr (9.04.2013, M6.3, Left) and the Sistan-Baluchestan (16.04.2013, M7.8, Right) Earthquakes

The European-Mediterranean Seismological Center (EMSC) derived event Perceived Intensity Maps, based on 50 and 390 automatically collected responses (Figures 3). While the Perceived Intensities (PI) from Bushehrs' Earthquake are estimated at PI = 4 for Abu Dhabi and PI = 5 for Dubai, they are for a degree higher for Sistan-Baluchestan Earthquake (Southern Gulf coast including Indian Ocean Coast up to Muscat, PI=5; Kuwait, PI=4; Musandam Peninsula, PI=6).

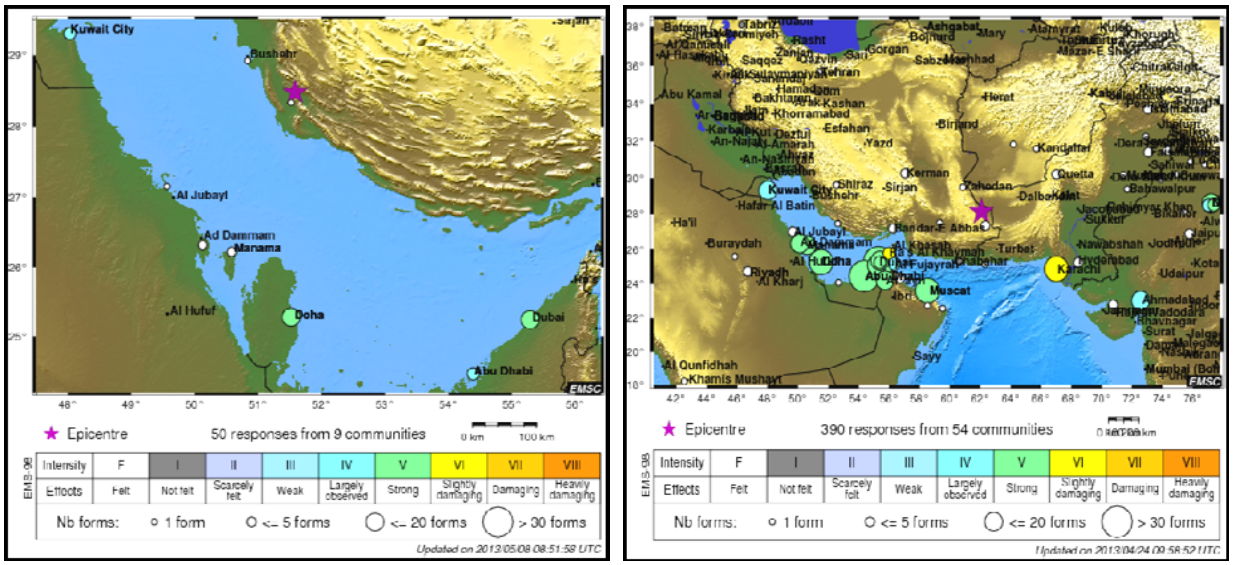


Figure 3. Perceived Intensity of 2013 Bushehr (Left) and 2013 Sistan-Baluchestan Earthquakes (Right)
Source: EMSC

3. ADSHRAs' SEISMIC AND STRUCTURAL HEALTH MONITORING COMPONENTS

To assure and maintain stable development of Abu Dhabi Emirate, disaster free living environment for its citizens and targeted quality of life, the Municipality Abu Dhabi City in 2008 initiated conceptualization of the Project "Assessment of Seismic Hazard and Risk in Emirate of Abu Dhabi (ADSHRA)".

Endeavoured in creating the Abu Dhabi System for Seismic Risk Monitoring and Management, the Project has been primarily focused on seismic sector. Being under the implementation over the last 24 months, the Project, in most effective and technically and scientifically consistent manner, integrates the state-of-the-art know-how, technology and data for developing a sound strategy and superior policies for protecting the current and planned development against adversity of potential environment impacts.

Compliant with the Abu Dhabi Municipality (ADM) vision: *To ensure a superior quality of life and a sustainable environment for Abu Dhabi residents*, ADSHRA assured:

1. Installation of Seismic monitoring for disaster risk management and reduction by deploying:
   - Permanent accelerograph network of fifty (50) stations (150 channels) and
   - Structural Health Monitoring Systems (204 channels in total) in unique structures selected within the urban areas of:
     - Abu Dhabi Municipality (5 structures, 3 x 36 + 2 x 24 channels = 156 channels)
     - Al Ain and Western Region Municipalities (2 structures, 2 x 24 channels = 48 channels)
   - Seismic monitoring for development and maintenance of 3D Seismic Simulation Model for simulating long-period seismic waves and triggering the Permanent accelerograph network by deployment of:
     - A network of four (4) stations consisting of three-component broad-band sensors and triaxial accelerometer unit (4 x 6 channels = 24 channels)
2. Establishment of UAE Ground Shaking Map (UAE-GSM) System
3. Establishment of the Seismic Design Parameters Web in a support to earthquake resistant architectural and structural design and construction practice
4. Seismic risk and loss assessment of:
   - Two Critical Importance Infrastructural Systems, and
   - Urban built environment

5. Development of reliable seismic data base as a major instrument for seismic risk monitoring and management
6. Establishment of disaggregated AD Seismic Risk Monitoring and Management Centre (AD-SRMMC) consisting of:
   - Two (2) Data, and
   - Five (5) Display Centres.

ADSHRA achieved Structural Health Monitoring (SHM) by seven 36 (3 buildings) and 24 (4 buildings) channel systems of ES-T and ES-U2 (Kinemetrics) sensors installed in selected buildings and REC-MIDS and OASIS on-site data analysis and display system.

ADSHRAs' SHM systems provide near-real time information about how buildings move and distort during shaking and where possible damage are likely to occur. Algorithms check for variations in movements of a building structural system and its vibration characteristics, for travel time of seismic waves between foundation and roof, and for exceedance of the building's seismic design capacity. If the damage detection algorithms match pre-set thresholds (Table 3), alarm messages are automatically sent.

Listed information allow rapid assessment of building safety in the aftermath of a major quake and support decisions on necessary repairs, replacements, and other maintenance and rehabilitation measures. In the long run, ADSHRAs' SHM systems also monitor the building's structural components for indications of deterioration and fatigue, enabling the building to be made more resilient and sustainable through improved maintenance.

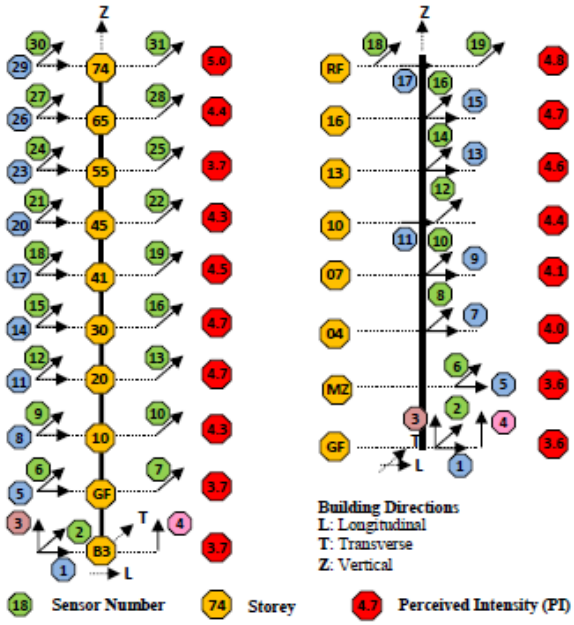


Figure 4. SHM Sensor Disposition and Storey Distribution of Perceived Intensities in High-rise and Ultra Tall Building in Abu Dhabi

Table 3. Building Performance and Alarm Treshold Levels ASCE 41 (2007)

	Alarm Level		
Parameter	**Level 1**	**Level 2**	**Level 3**
Story drift ratio:	0.005	0.010	0.020
Safety level:	**IMMEDİATE OCCUPANCY (IO)**	**LİFE SAFETY (LS)**	**COLLAPSE PREVENTİON (CP)**
Earthquake probability level:	50% likelihood in 50 years	10% likelihood in 50 years	2% likelihood in 50 years
Earthquake return period:	72 years	475 years	2475 years

Recordings from structural-health monitoring systems are critical to designing safer buildings and in preventing loss of life. In particular they help engineers to:

- assess building safety immediately following a damaging quake,
- understand how damage to structural and nonstructural components occurs from strong shaking,
- evaluate and improve earthquake-resistant design techniques and methods for predicting the seismic performance of structures,
- understand the building intrinsic safety and risk levels relative to adopted level of acceptable risk, and
- improve, if needed, earthquake-resistant design provisions of building codes and the structural design and construction practice.

Besides the listed post-event objectives, of solely engineering nature, SHM recordings are capable of providing proactive, near-real time, information relevant for emergency decision making process of human distress, i.e. on intensities the building inhabitants perceived (PI) during the building shaking.

4. PERCEIVED INTENSITY FROM STRUCTURAL HEALTH MONITORING SYSTEMS

The AD-SRMMC cyber platform in a real-time efficiently recorded both earthquakes and instantly provided all necessary emergency decision elements.

The UAE-GSM calculated for M6.3 Bushehr Earthquake is provided in 6 minutes following the arrival of seismic waves in the territory of Abu Dhabi Emirate (Figure 1). The GSM Intensity calculated for Abu Dhabi island is 1.6. At MMI Intensity II "A few people might notice movement if they are at rest and/or on the upper floors of tall buildings" (Table 2). However, human distress drained high-rise and tall buildings which is in a direct collision with description for MMI = II of Table 2.

Literature offers various relations interlinking instrumentally recorded peak (P) ground (G) motion parameters (PGA, PGV, PGD,) and Instrumental intensity. For building occupants the 'ground' is a floor where they have been exposed to shaking. Assuming that a floor movement is known, the same relations can be used for estimating the floor intensities based on recorded peak (P) floor (F) motion parameters (PFA, PFV, PFD).

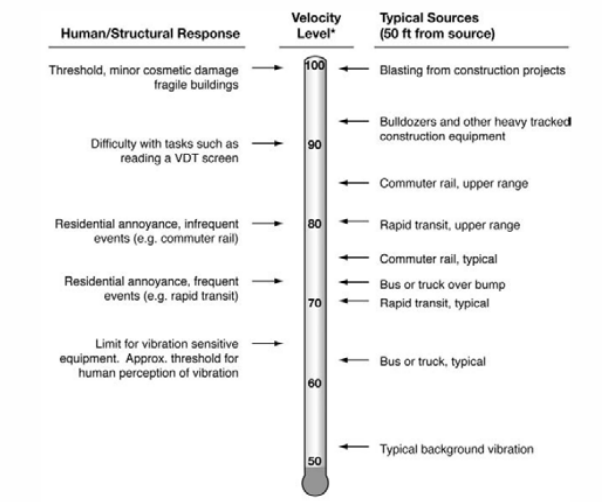
PIs' from real-time recordings taken at ADSHRAs' SHM instrumented buildings are calculated based on Aptikaev (2005, 2010) relations, more precise, the relation 2:

$$\log(\text{PFA}),\ \text{cm}/s^2 = -0.755 + 0.40\,\text{PI} \pm 0.39\ (0.25),\ \text{correlation coefficient: } 0.82 \quad (1)$$

$$\log(\text{PFV}),\ \text{cm}/s = -2.230 + 0.47\,\text{PI} \pm 0.33\ (0.20),\ \text{correlation coefficient: } 0.84 \quad (2)$$

$$\log(\text{PFD}),\ \text{cm} = -4.260 + 0.68\,\text{PI} \pm 0.65\ (0.33),\ \text{correlation coefficient: } 0.81 \quad (3)$$

Figure 4 summarizes the perceived intensities derived based on 2013 Bushehrs' Earthquake recordings obtained from two SHM monitored buildings in Abu Dhabi (results for other buildings are not presented). The estimated PIs are: PI = 4.45 (max 5.0) for 74 storey and PI = 4.43 (max 4.8) for 18 storey building, and are in fair agreement with testimonies posted on social media and/or reported by Internet News (Annex A) as well as results derived by EMSC (Figure 3, PI=4 for Abu Dhabi).



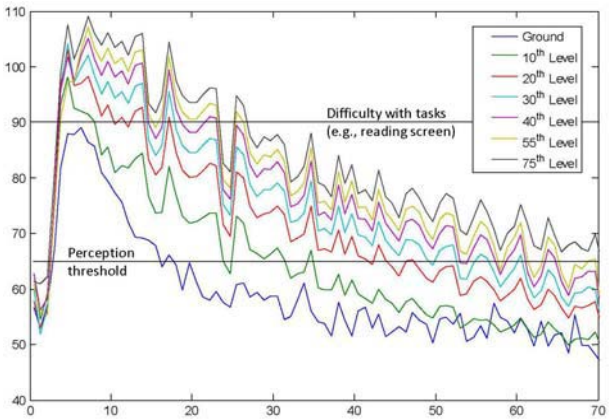


Figure 5. Top Floor Vibration Level of one of SHM Instrumented Abu Dhabi Tall Buildings

Perceived intensities PI = 4+, generate effects (Table 2) that fully explains the behaviour of building occupants and the distress generated. While EMSC estimates (Figures 3) are close, they were available long after the human distress emergency was over, thus were practically unusable as information supporting the human distress management process. More detail insight on tall (~ 300m in height) building shaking generated by the same earthquake is presented in Figure 5. The shaking

above the human perception (velocity level 65 in/s) threshold lasted for more than 70 minutes, whereas shaking producing difficulties with tasks such as reading a VDT screens (90 in/s) lasted for 18 minutes. From these considerations there is no wander why the inhabitants reaction was panicked flee from buildings, irrespective of the fact that generated interstory drifts (ID) were significantly below the Immediate occupancy level (Figure 6), thus, during and after the earthquake, the building has been perfectly safe.

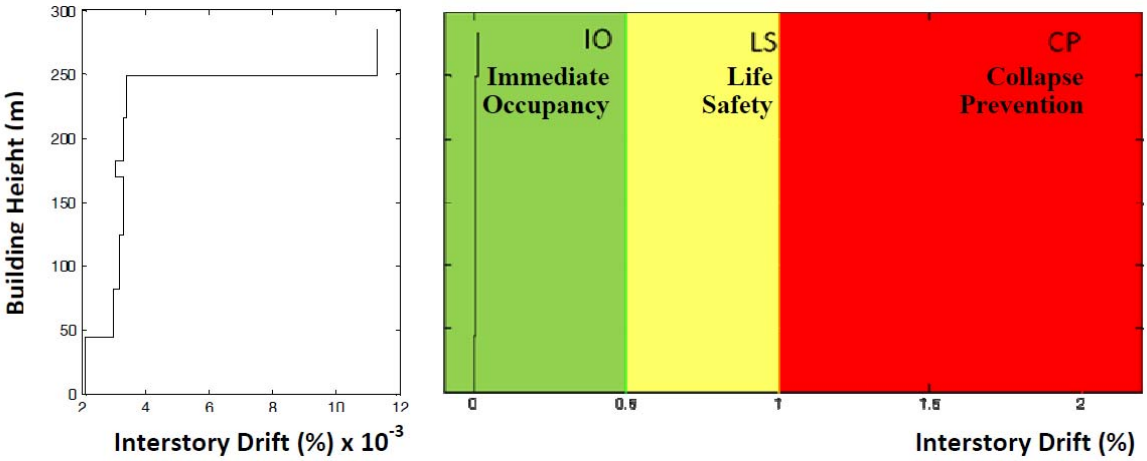


Figure 6. Interstory Drift of One of Five SHM Instrumented Abu Dhabi Tall Buildings

5. CONCLUSIONS

The post-event human distress in Gulf countries generated by M6.3 Bushehr and M7.8 Sistan-Baluchestan Earthquakes demonstrated that:

- the classic USGS ShakeMap concept providing instrumental ground intensities only cannot efficiently be used as an emergency information quantifying the human perception on the shaking intensity of high-rise and tall buildings and as a measure quantifying the human distress,
- SHM systems can efficiently provide rapid, near-real time conjugated information on the building shaking intensity (Perceived Intensity, PI) and the post-event building safety based on the level of deformation the building experienced during the shaking (interstory drift, ID), and
- the PI/ID are parameters that emergency systems can operatively use for mass management of human behaviour and distress (PI) and deciding the post-event building safety status (Immediate Occupancy, Life Safety or Collapse Prevention) as well as define operative measures accordingly.

For management of urban scale post-event human distress and building safety status problems, the extension of presented concept is needed, in particular since the number of SHM equipped buildings is relatively low. Work along that direction is underway.

REFERENCES

Sandi, H., F. Aptikaev, O. Erteleva, I.-S. Borcia and V. Alcaz (2010). An Actual Need to Modernize the Concept of Seismic Intensity, CONSTRUCTII– Nr. 2 / 2010 (Proc. of 14th ECEE, Ohrid, 2010).

ASCE (American Society of Civil Engineers) (2007) Seismic Rehabilitation of Existing Buildings, ASCE/SEI 41, Washington, DC, USA.

http://www.emsc-csem.org/Earthquake/217/M-6-3-SOUTHERN-IRAN-on-April-9th-2013-at-11-52-UTC

http://www.emsc-csem.org/Earthquake/218/M-7-8-IRAN-PAKISTAN-BORDER-REGION-on-April-16th-2013-at-10-44-UTC

http://www.khaleejtimes.com/kt-article-display-1.asp?xfile=data/nationgeneral/2013/April/nationgeneral_April319.xml&section=nationgeneral

Annex A. Testimonies on Effects Perceived in Gulf States from Bushehr (9.04.2013, M6.3)

SHARIJAH, UAE:
"Crescent Tower, Bohaira Cornich, Sharjah also had tremor".
"I was in Sharjah sleeping then I woke up to something shaking at first I thought it was kids making a bunch of noises until I saw my lamp shaking so me and my wife ran out the building immediately."
"I felt mild tremors in my flat in Al Qasmiya Sharjah the lamps were swinging mildly; it lasted for two minutes. It was scary as well since I live on a higher floor."

ABU DHABI, UAE:
"I'm in Abu Hail, Diera and our flat's on the **3rd floor**! Everybody's awake at 4pm and on one had ever felt there was a tremor. …"
"I live on **14th Floor** building in Abu Dhabi felt tremor around 3:55pm.I was in kitchen doing work i felt the tremor & suddenly door chimes ringing & holder on top was moving."
"The quake was back and forth and i felt it in my flat on **15th floor** in Abu Dhabi"
"I feel fully shaking my building where I'm staying in **16th floor** Abu Dhabi"
"At West Tower Abu Dhabi mall, I noticed when the door and the glass windows suddenly shaking, back &forth. That lasted 8 seconds. …"
From Rolla to Buhaira Corniche, people living in high-rise buildings ran onto the streets. The Abu Dhabi Investment Authority building on the Corniche was evacuated as fire alarms were triggered. "I was on the **26th floor** when the whole building started to shake."
"Felt nothing at all....living in a villa"

DUBAI, UAE:
"I am working in high rise building in TECOM and my office is on **21st floor** i thought I was dizzy but turns out it was actually an earthquake!!!!! It was a horrible feeling..."
"I was in the balcony smoking on the **30th floor** and was rocking back and forth thought I had a headache"
"In Deira creek we could feel the same giddiness. It was a tuff task to run down **15 floors** in no time"
"OMG I felt the earthquake in Dubai (Sh. Zayed Road)...It felt like I was on a boat, but i was in my apartment on the **26th floor**...so weird!!! I thought it was just me..."
"Marina **29th Floor**. Curtains and lamp was swinging felt very odd. Got sick and ran outside as we thought the building will fall. On the ground floor they thought we are insane as they didn't feel anything"
Jebel Ali Downtown galleries. "I felt the building shaking. It felt like the roof was going to fall on me. I then stood up, and felt dizzy, then headed for the stairs."
"Everyone started freaking out." In Dubai Media City, employees evacuated Al Thuraya Tower after the alarm was sounded. "We all felt it and then heard the alarm sound."
"The security shut down the elevators. Everything seemed to be crazy, including the traffic on the roads. People were just going left and right. It was chaos."
"I felt absolutely nothing! Had no idea about till this morning. I live in JVC Dubai. A villa"
"No tremors felt at the Burj Khalifa.

DOHA, QATAR:
"We also feel like shaking in Qatar, Doha city"
Yup I felt. I was at home...First I felt lil dizzy, but it was horrible suddenly I saw all my tea tables n comp were shaking...then I realized that it was earthquake.
"Driving home and buildings evacuated everywhere."
Doha news: "Thousands of people were evacuated from office and residential towers across Doha after tremors left many residents feeling a shaking sensation - in some instances for up to 30 to 40 seconds."

BAHRAIN:
Aftershocks felt in Manama, Bahrain up to morning of 14th April.
"My office was evacuated and the Al Seef area in Manama was reportedly quite severe. It wasn't vibration, but actual swinging."
Al Wattan daily: Bahraini authorities on 9.04.2013 (Tuesday) evacuated a number of high-rise buildings in the capital Manama after tremors were felt as a result of an earthquake in southern Iran. The tremors were mostly felt in areas of Juffair, Adliya and Um Al Hassan in the capital (Manama). According to the report, among the evacuated buildings were the World Trade Center, Bahrain Financial Harbor and Bahrain Chamber of Commerce and Industry.

ALKHOBAR, RASTANURA, JUBAIL, DAMMAM and KHOBAR, SAUDI ARABIA:
ALKHOBAR, "Feel very powerful intensity here in Alkhobar Saudi Arabia"
RASTANURA, "We felt also the earthquake here in Rastanura, Saudi Arabia office 3rd floor building"
JUBAIL, "We Also feel like shaking in Jubail"
DAMMAM, "A large number of expatriates and citizens gathered near the Sheik Building in Dammam, which is the downtown and commercial hub of the city; they seemed to be in a sense of extreme fright due to the minor trembles that took place in some of the buildings near Sheik."
KHOBAR, Several places in this city experienced trembles that put many on edge. Some of the high-towering buildings like Juffali tower, and others were affected by the strike of the earthquake. Although no major casualties have been reported, the windows and ceilings of a few buildings including Juffali tower were slightly damaged and walls cracked. All the residents were evacuated immediately upon the occurrence of the seismic shudder. The people rushed out of the buildings and got together in nearby lawns and lanes looking at the skyscrapers and towers.