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REFLECTION ON SOME 21ST CENTURY EARTHQUAKES

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Abstract

This paper attempts to reflect on the question of how have we fared over the seismic events in the 21st century? By means of select events, some of the important recent lessons are highlighted, and areas for further improvement of our capacity in mitigating earthquake impacts are explored:

- Increased Potential Earthquake Casualty with Rapid Densification of Population in Vulnerable Urban Centres - This trend is particularly acute in developing countries, where the seismo-tectonic setting of urban site and poor condition of built environment often constitute a physical death trap for its inhabitants;
- Under-estimation of Seismic Hazard - Geological input in seismic hazard evaluation sometimes lags behind geoscience advancement. In other words, incorporation of appropriate seismic criteria for the design of building and infrastructure is often promulgated only after a devastating earthquake.
- Severity of Traditional and Compounded Earthquake Secondary Impact - with increased population density and modern industrial development, the scope and severity of earthquake secondary impact are often underestimated and inadequately prepared for;
- Advancement of Earthquake Monitoring and Understanding - the advancement continues, especially for a few major seismic events both before and after their occurrences, although many challenges remain; and
- Evolution of Societal Response to Earthquake - with increasingly sophistication of modern society and ongoing improvement of earthquake knowledge, our societal response to a significant seismic event is also undergoing inevitable changes. Some observations of these changes are briefly discussed.

Earthquake is a natural hazard whose impact on our life is influenced to some degree by the development of our civilization. Although earthquake per se does not kill, failures of natural and/or built environment caused by it, do. Wittingly or not, the high population density in our cities, attainable because of our technological development, also exposes us all to increased vulnerability to earthquake destruction. Presented herein are some issues worthy of our collective reflection.

Keywords: major earthquake; secondary impact; earthquake hazard; damage mitigation; effective communication

1. Earthquake Impact Dictated by Socio-Economic Development

In the beginning decade and a half of the 21st century, the world has experienced about 270 (up to Sept. 2016) earthquakes with magnitude equal to or greater than 7. This paper highlights some features of representative seismic events and discusses their implications in our ongoing pursuit of minimizing earthquake impacts. Table 1 presents a summary of relevant earthquake and damage data for nine 21st-century earthquakes discussed herein. The affected countries in Table 1 range in varying degrees of developing phase. In general, wealthy countries with advanced development tend to suffer relatively low casualties but high economic loss in a major earthquake. In contrast, poor, developing countries suffer sometimes several orders-of-magnitude higher casualties with relatively low economic loss in a comparable event. The contrast in the respective outcomes lies in the earthquake-resistant capacity of the built environment and sophistication level of the industrial-commercial establishment in the affected areas. As the trend of urbanization quickens, population density is increasing rapidly in cities of various sizes around the world. Thus, without improvement the impact of future earthquake at a given site is expected to increase with time in proportion to the increase of population density [1, 2]. Globally the historical trend of rising earthquake fatalities since 500 BC, as shown on Fig. 1, is expected to persist, or even accelerate if we do not learn seriously our lesson from past disasters.

Table 1 – Relevant Earthquake and Damage Data for Nine 21st-Century Earthquakes

Date (Local Time)	**Earthquake Location**	**Type**	**Focal Mechanism**	**Peak Acceleration Intensity, MMI**	**Special Features**	**Casualties**	**Damages General**	**Lifelines**	**General References[1]**
2003 Dec. 26 (5:26 am)	**Bam Southern Iran**	Crustal	Mw 6.6, depth 10 km reverse and right-lateral strike-slip faulting on the north-south oriented Bam fault	Vertical acceleration of 0.98 g Modified Mercalli Intensity IX at Bam, VIII at Baravat and V at Kerman	Maximum vertical acceleration of 0.98 g recorded at Bam, Surface faulting on the Bam Fault observed between Bam and Baravat, Destruction of the 2,500-year old, the world largest mud-brick Arg-e-Bam citadel	High at least 30,000 killed and 30,000 injured 45,000 to 75,000 homeless	Over 85 % of buildings were damaged or destroyed	Over 85 % of infrastructure were damaged or destroyed	USGS 2004 Bam EQ Poster
2004 Dec. 26 (7:58 am)	**Sumatra Indonesia (Indian Ocean)**	Inter-plate	Mw 9.1 to 9.3, depth 30 km 1300 km x 150 km rupture zone defined by aftershocks, min. 500 km rupture length at main shock, max. 20 m fault displacement Sea floor uplifted several metres	Modified Mercalli Intensity ≤ X+	Heavy casualty in countries around Bay of Bengal and Indian Ocean due to no warning of incoming tsunami Tsunami run-up 2 to 5 m, up to a max. of 31 m, max. flow depth >9 m and inundation up to 3 to 4 km inland Earthquake damage in Aceh, North and West Sumatra	Very High death ~180,000+ to 230,000+ injured ~125,000 missing ~46,000 displaced ~1.69 million	Severe Economic loss ~ US $13 billion Impact on tourism	Moderate Tsunami inundation - main cause of lifelines damage in affected areas	ASCE 2007 EERI Newsletter Mar - Jul 2005 EERI Spectra 2006 BSSA 2007 USGS 2004
2008 May 12 (2:28 pm)	**Wenchuan China (Asia Continent)**	Crustal	Mw 7.9, depth 19 km Thrust/strike-slip rupture along main (200 km long, 2-4 m offset) and splay (50 km long, 0.5-2 m offset) fault	≤ 0.98 g Modified Mercalli Intensity up to X to XI	Widespread earthquake shaking, massive landslides, debris flows and formation of landslide dams Maximum offset (main fault 11 m and splay fault 3.5 m) Building code design requirements under-estimate significantly the seismic demand Substantial portion of existing building stocks deficient in seismic resistance	Very High death 69,195 injured 374,643 missing 18,392 displaced 5 million	Severe Economic loss ~US $120 billion Collapse of and damage to buildings	Severe 53,000 km of roads damaged Bridges collapsed, damaged Power lines, communication systems demolished, disrupted 47,643 km of pipelines and 8,426 water treatment plants damaged	EEEV 2008 EERI Newsletter Oct. 2008 BSSA 2010 USGS 2008
2010 Jan. 12 (4:53 pm)	**Haiti (Caribbean Sea)**	Crustal	Mw 7.0, depth 13 km A combination of reverse and left-lateral strike- slip faulting related to the Enriquillo-Plantain Garden fault system, ruptured zone about 30 km by 15 km, with left- lateral slip fault displacement, and max. moment release in the first 10 secs.	Estimated ~0.3 to 0.45 g Modified Mercalli Intensity IV to VIII	Heavy casualties due to collapse of poor-quality (unreinforced masonry or non-ductile reinforced concrete) building stocks Liquefaction and lateral spreading, landslides and rockfalls contributed to damage	Very High death ~233,000 to 250,000 ~ 1,000 from cholera injured ~300,000 homeless ~1 million	Severe Economic loss ~ US $7.8 billion	Main port suffered extensive damages, including collapse of piers and submerged cranes	EERI Newsletter Apr./May 2010 USGS 2010 USGS/EERI 2010
2010 Feb. 27 (3:34 am)	**Maule (Offshore Bio-Bio) Chile (South Pacific Ocean)**	Inter-plate	Mw 8.8, depth 35 km Rupture zone 500 km by 100 km >0.05 g duration over 1 min in general, and over 2 min in Concepcion area Horiz. displacement up to 3 m to west along coastline from south to north, up to 2 m uplift in the south, 0.5 m subsidence in the north	Up to 0.65 g Modified Mercalli Intensity up to VI to IX	Tsunami run-up height in the range of 3 to 9 m Coastal uplift and subsidence Numerous aftershocks including 19 in the range of Mw 6.0 to 6.9 within the first month	Low death ~521 more than 200 due to tsunami, missing 56	Severe Economic loss ~ US $30 billion	Liquefaction caused significant damage to power transmission towers, water and waste water systems Earthquake caused damage to and extended outage of oil refineries Tsunami damage to ports and bridges	GEER 2010 EERI Newsletter Jun. 2010 USGS 2010

Table 1 – Relevant Earthquake and Damage Data for Nine 21st-Century Earthquakes (Cont`d)

Date (Local Time)	Earthquake Location	Type	Focal Mechanism	Peak Acceleration Intensity, MMI	Special Features	Casualties	Damages General	Lifelines	General References[1]
2010 Sep. 4 (4:35 am)	**Darfield (Canterbury) New Zealand (South Pacific Ocean)**	Crustal	Mw 7.0, depth 10 km Reverse fault with strike-slip right- lateral (maximum 4 m) and vertical (maximum 1 m) displacement, about 30 km surficial rupture, and 40 km west of Christchurch	Up to 0.74 g horiz. with even higher vert. acc. in epicentral area Modified Mercalli intensity in epicentral area VIII-IX in Christchurch VI to VII	Widespread liquefaction and lateral spreading Poor performance of unreinforced masonry buildings Non-structural damage to building components and contents Repair of many damaged structures in progress when the Mw=6.1 aftershock struck	Nil 1 died of heart attack 2 injured by fallen objects	Economic loss ~ US $3 billion Structural damages to unreinforced masonry buildings and non- structural damages to other buildings Liquefaction caused significant building damage	Liquefaction and lateral spreading caused significant damage to water and waste water systems Underground voids created by loss of sand due to sand ejection from ground	EERI Newsletter Nov. 2010 USGS 2010
2011 Feb. 22 (12:51 pm)	**Christchurch New Zealand (South Pacific Ocean)**	Crustal	Mw 6.1, depth ~5 km Oblique blind thrust fault with up to 2.5 m slip displacement About 14 km long sub-surface rupture within 10 km of Christchurch city centre	Maximum spike to 1.5 g near epicentre and up to 0.72 g near city centre (for about 8 sec.) Modified Mercalli Intensity up to VIII in Christchurch	Aftershock of Sept. 4, 2010 Darfield Earthquake (about 5 months later), Substantial damage to the central business district (CBD) of Christchurch due to closer distance to earthquake and weakened structures by the main shock, Widespread liquefaction in the CBD and eastern subsurbs, Landslides and rockfalls in Port Hills.	Low 184	Economic loss ~ US $ 16 billion Collapse of and damage to buildings Liquefaction caused significant building damage	Extensive lifelines damage due to liquefaction and lateral spreading, including: roads and highways, power distribution systems, water and wastewater lines and drainage facilities	EERI Newsletter May 2011 USGS 2011
2011 Mar. 11 (2:46 pm)	**Tohoku-Oki (East Japan) Japan (North Pacific Ocean)**	Inter-plate	Mw 9.0, depth 32 km Rupture Zone 300 km by 150 km Preceded by a series of foreshocks ranging from Mw 6 to 7.2 since March 9	Maximum spike to 3.0 g Modified Mercalli Intensity up to VI to VIII	Tsunami run-up height 4 to 8 m, with maximum up to 38 m Tsunami and earthquake damaged Fukushima Dai-Ichi nuclear power plant, power and cooling systems, resulting in reactor core rods meltdown and eventual abandonment of the plant, as well as the problem of prolonged radiation contamination, Breach of a 17 m high earthfill dam.	High death 15,188 injured 5,337 missing 8,742 homes damaged ~200,000	Economic loss ~ US $300 billion 7,735 schools and >300 hospitals damaged	Fuel rods meltdown at a nuclear power plant Earthquake and tsunami destroyed many communities together with lifelines, such as power, transportation including bridges, communication, water and waste-water system Bridge deck failures due to tsunami uplift	JSCE 2011 PEER 2011 USGS 2011 EERI 2011
2015 April 25 (11:56 am)	**Gorkha, Nepal (36 km east of Khudi)**	Inter-plate	Mw 7.8, depth 15 km thrust faulting over rupture zone ~120x80 km, directing eastwards from hypocentre towards Kathmandu. Main Himalayan Thrust fault appears to accommodate most plate convergence across the Himalaya, and growth of Himalayan topography may occur mainly during post-seismic phase.	Modified Mercalli Intensity near epicentre X+, and VIII in Kathmandu.	Included in the casualties are 180 people killed from the collapse of Nepal's historic Dharahara Tower and 20 people killed and 120 injured from an avalanche at the Mount Everest Base Camp.	High at least 8,670 people killed, 380 missing, 17,900 injured, 500,720 houses destroyed and 269,200 damaged in Nepal in the main shock and the M 7.3 aftershock on May 12.	Damage estimates exceed $5 billion US dollars.	Landslides occurred and roads and power lines damaged in Nepal.	USGS 2015 Nepal Eq. Poster NG 2016

Notes: 1. USGS - U.S. Geological Survey; ASCE - American Society of Civil Engineers; NG – Nature Geoscience
EERI - Earthquake Engineering Research Institute; BSSA - Bulletin of Seismological Society of America
EEEV- Earthquake Engineering and Engineering Vibration; GEER- Geotechnical Extreme Events Reconnaissance
JSCE- Japan Society of Civil Engineers; PEER- Pacific Earthquake Engineering Research Center

2. Under-estimated Seismic Hazard

Site geological input is fundamental to establish an appropriate seismic setting for the design of building and infrastructure. This input is usually embedded in a modern building or structure code in terms of seismic design load. However, our understanding of site seismicity faces two types of uncertainty: epistemic (related to our current state of knowledge) and aleatory (related to chance). The epistemic uncertainty will reduce with the advancement of our knowledge, while the true picture of "chance" will only become clearer when reliable long-term seismological including paleoseismic data are being collected and analyzed. Thus, at any given time, the prevailing code is a working model that contains the above dual uncertainties. Stein et al. [3] discussed issues on when and how to revise an earthquake hazard map after an event yielding shaking larger than anticipated. Critical in their discussion is the relative length of the average recurrence time of the event versus the intended time window for the hazard map's application. Another issue is the consequence of the event's impact. Two recent events are presented below to illustrate the tragic consequence, when these uncertainties led to severe direct and indirect destructions in the affected regions.

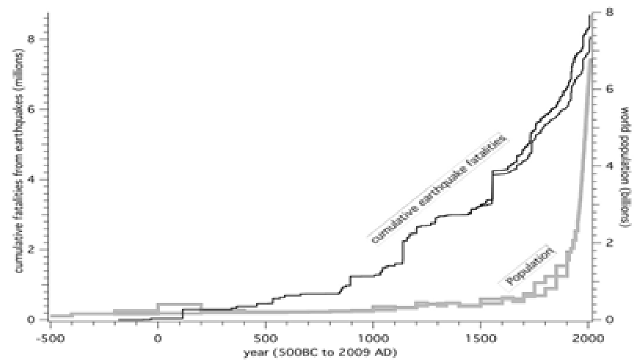


Fig. 1 - Earthquake fatalities since 500 BC compared to estimated global populations (from Bilham 2013)

2.1 Sudden Arrival of a Newly Recognized Threat - 2008 Wenchuan, China Event

Densmore et al. [4] summarized their multi-year study on the faults in the Longmenshan Fold and Thrust Belt flanking western Sichuan Basin to clarify the activities since the late Cenozoic era and kinematics of the major faults along the Tibet plateau eastern margin (see Figs. 2 and 3). In the study, they combined the use of field mapping, image interpretation, surveying of offset geomorphic markers, trenching and cosmogenic nuclide dating. They concluded that the Beichuan and Penguan faults have experienced surface rupture during the latest Pleistocene and at some locations during the Holocene. Because these faults are sufficiently long to sustain a strong ground-shaking earthquake, they recognized them as potentially serious sources of regional seismic hazard. Their paper was published on July 17, 2007 in Tectonics journal. About 10 months later, their newly recognized threat materialized in the devastating magnitude Mw 7.9 Wenchuan earthquake on May 12, 2008 [5], leaving no time for the incorporation of their critical finding in the prevailing building code, which significantly under-estimated the regional seismicity.

2.1.1 Wenchuan Earthquake

Sichuan province is located in the southwest of China. On a continental scale, the regional seismicity is a result of northward convergence of the India plate against the Eurasia plate at a rate of about 50 mm/yr. The plate convergence is broadly accommodated by the uplift of the Qinhai-Tibet highlands as well as the extrusion of crustal material to the east away from the uplifted plateau (see Fig. 2). At the Longmenshan, the eastern flank of the Tibetan Plateau rises 6 km above the Sichuan Basin within a short distance of 100 km.

The Wenchuan earthquake occurred as a result of fault-slip motions in the Longmenshan Fold and Thrust Belt, a northeast striking dextral-lateral, reverse (or thrust) fault system on the northwestern margin of the Sichuan Basin. The earthquake reflects tectonic stresses resulting from the convergence of weak crustal material slowly moving from the west Qinhai-Tiebet Plateau against Yantze Craton, a strong crust underlying the Sichuan Basin and southeastern China [5] (see Fig. 3).

2.1.2 Improved Understanding of Longmenshan Seismicity

Considerable investigation activities were carried out to improve the understanding of the structure of the Lomenshan faults and the faulting mechanism of the Wenchuan EQ, including drilling deep holes at four locations of the Yingxiu-Beichuan and Guanxian-Anxian faults with maximum length up to 1548 m [6] (see Figs 4 and 5) as well as surface trenching for studying paleoseismic activities [7].

Liu-Zeng et al. [8] reviewed co-seismic ruptures of the Longmenshan thrust fault system in the 2008 Wenchuan EQ, and called for re-evaluation of the regional tectonic model as well as the regional seismic hazard by incorporating new knowledge gained from the 2008 event. Densmore et al. [9] reviewed the role played by late Quaternary upper-crustal faults in the 2008 Wenchuan earthquake. They observed that the Wenchuan surface rupture followed geological faults mapped on the basis of bedrock lithology, and inferred that active deformation along the plateau margin is accommodated by partial reactivation of a complex network of pre-existing faults.

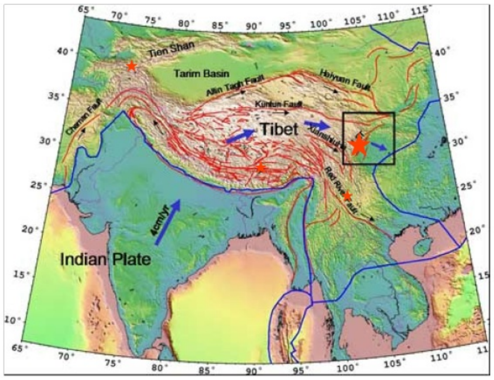


Fig. 2 - Tectonic Setting of Qinhai-Tibet Plateau and Sichuan Basin (from Geoportalen.no 2008)

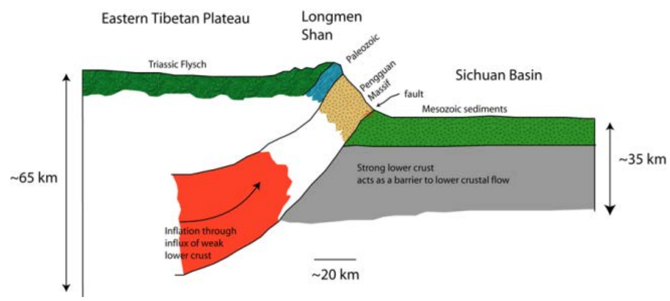


Fig. 3 - Section through Qinhai-Tibet Plateau and Sichuan Basin (from MIT 2008).

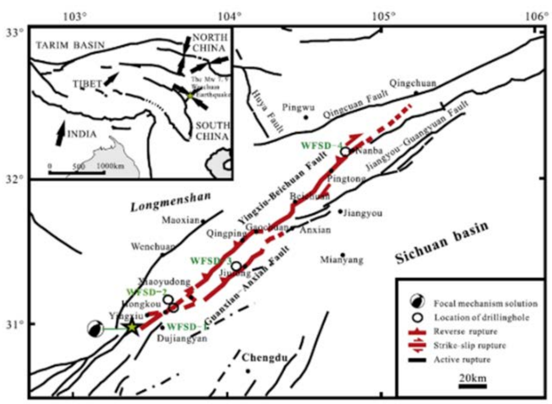


Fig. 4 - Location of Deep Drill Holes for Longmenshan Fault System Investigations (Nie et al. 2013)

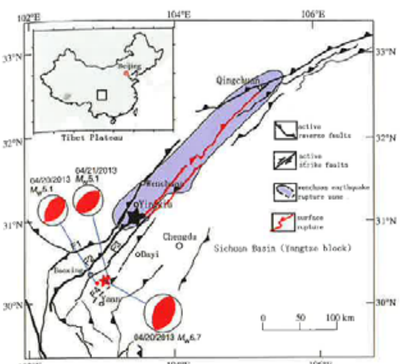


Fig. 5 - Tectonic Setting of Longmenshan Fault System (Han et al. 2014)

In his preface to a special issue of Tectonophysics on the great 12 May 2008 Wenchuan Earthquake (Mw7.9), Yin [10] provided an overview of 22 papers on observations and unanswered questions regarding the earthquake. He indicated that the mechanism for the formation of the eastern Tibetan plateau is dominated by lithospheric-scale pure-shear contraction (vertical thickening) associated with a weak and highly deformable underlying mantle lithosphere. Similarly, Zhang and Engdahl [11] provided an overview of 24 papers on great earthquakes in the 21st century and geodynamics of the Tibetan Plateau.

The Longmenshan seismicity is characterized by two seemingly conflicting features: (1) long recurrence intervals of regional earthquakes; and (2) low inter-seismic deformation. Zhang [12] argued that these could be explained by the relatively high rock strength in the source area resulting in tight inter-seismic locking of the fault and a very gradual process of stress build-up. Thus, other slowly slipping faults in similar geological setting should be identified as potential sources of high seismic hazard. Figure 6a shows low strain rate across the Longmenshan fault zone and a simplified section of the causative fault zones from the eastern Tibet Plateau to Sichuan Basin. Figures 6b and 6c show the photos of the fault rupture near a school at Bailu during the Wenchuan EQ and subsequent trench investigation effort at Bailu following the event.

2.1.3 2013 April 20 Mw 6.6 Lushan Earthquake

Nearly five years after the Wenchuan EQ, a powerful Mw 6.6 Lushan EQ occurred near the south segment of the Longmenshan fold belt about 90 km southwest of the Wenchuan EQ epicentral region [13] (see two stars in Fig. 5 for locations of the two EQs). The Lushan earthquake caused about 200 fatalities and over 11,000 injured [14]. Yao and Peng [15] prefaced 8 papers covering the Lushan earthquake and its relation with the Wenchuan earthquake and the impact of this relation to the seismic hazard in the region of the Longmenshan fault south segment. Although considerable discussions have taken place on whether the Lushan EQ was an aftershock of the Wenchuan EQ or an independent event, the significant interaction between the two events seems to be widely recognized.

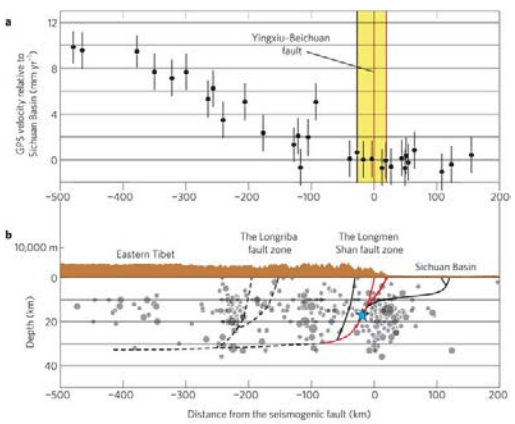


Fig. 6(a) - Deformation in Longmenshan Fault Zone
(http://www.nature.com/ngeo/focus/wenchuan-earthquake/index.html#editorial)

Fig. 6(b) - Fault Rupture through a School at Bailu
(http://www.nature.com/news/2009/130509/full/459153a.html)

Fig. 6(c) - Trenching Fault at Bailu

The crustal stress and seismic hazard along the southwest segment of the Longmenshan thrust belt had been evaluated by measuring in situ stress with hydraulic fracturing in four boreholes at the Ridi, Wasigou, Dahegou, and Baoxing sites in 2003, 2008, and 2010 [16]. The evaluation indicated that the in situ stress in this segment remained sufficiently high, especially in the Baoxing region, where the Mw 6.6 Lushan EQ occurred on April 20, 2013.

2.2 Under-estimated Earthquake and Tsunami Threat - 2011 Tohoku, Japan Event

Although subduction earthquake threat in the Tohoku region of Japan has been well recognized, the fact that the 2011 March 11 Tohoku-Oki EQ was a magnitude 9 event seemed to have exceeded experts' expectation [17, 18]. Kagan and Jackson [19] asked a rhetorical question, "Tohoku Earthquake: A surprise?" By applying the moment conservation principle, they argued that the maximum magnitude in the order of 9 to 9.7 could be expected, when considering all the subduction zones in the world. Similarly, the maximum magnitude of 9 could be expected, when considering the specific subduction zone off the Tohoku region.

By default, the tsunami generated on March 11, 2011 became "too high" with runup of up to 40 m along the Sanriku coastline, and overpowered the defence measures along the affected coastal areas. About 18,000 people lost their life, 6,200 injured and 2,800 reported as missing. Damage wrought by the tsunami far exceeded that caused by the earthquake. The tsunami further overwhelmed the power and cooling systems at the Fukushima Dai-ichi nuclear power plants, triggered melt-downs of fuel rods and contaminated the surrounding land and ocean with nuclear radiation. This precedent-setting impact not only hindered initial emergency response in the affected areas, but also continues to demand ongoing care, maintenance and restoration to mitigate its long-term impact for the foreseeable future.

Bletery et al. [20] presented a single finite fault-slip model using joint inversion of complementary detailed data, including tele- and near-field seismic, high-rate and static GPS, seafloor geodesy and tsunami data. The model showed a patchy slip distribution with large slip (up to 64 m) mostly updip of the hypocentre near the trench.

Ikari et al. [21] performed shear tests on samples retrieved from the fault rupture zone obtained by the Japan Trench Drilling Project. Test results showed that the fault material exhibiting a full spectrum of fault-slip behaviour ranging from slow steady creep to fast unstable slip, consistent with the actual fault-slip behaviour during the 2011 earthquake.

3. Traditional and Compounded Earthquake Secondary Impacts

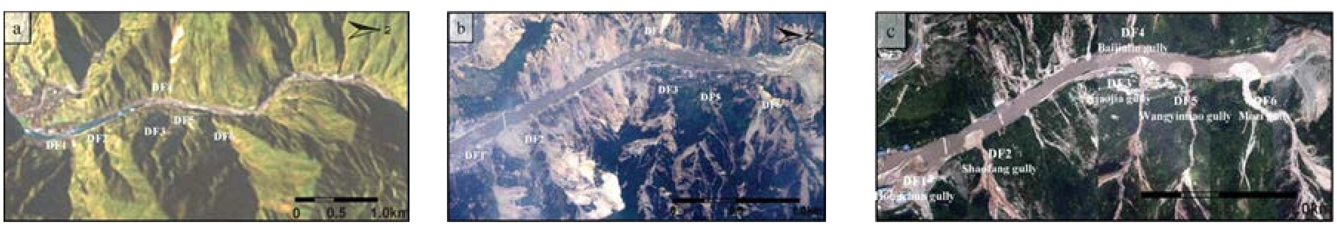
3.1 General

Traditional secondary earthquake impacts include tsunami, fire, landslide, debris flow and liquefaction, etc. With the development of modern industrial facilities, the failure consequences of some of these facilities are severe indeed. The facility failure could be caused by earthquake itself or any of its secondary impacts. The meltdown of 3 nuclear reactors at the Fukushima Dai-ichi power plant illustrated the danger of this type of compounded earthquake impact [22]. It set a precedent of earthquake-triggered nuclear incident. The long-lived radiation extends its impact beyond the immediate proximity of the power plant as well as further into the indefinite future. Other examples of compounded secondary impact include destruction of chemical plant, fuel and hazardous-waste storage facility and breach of major reservoir, tailings impoundment or landslide lake.

3.2 Prolonged Aftermath

3.2.1 Intensified Geo-hazards after Wenchuan Earthquake

After a major earthquake relatively loose landslide debris materials tend to perch metastably on steep terrains often remote from population centres. This latent geo-hazard waits to reveal its destructive force, when the debris gets re-mobilized by heavy and/or sustained rainfall. Right after a severe earthquake, there are so many urgent tasks requiring attention by the authorities and public. Unless special attention is focused on careful investigation of this potential hazard and actions taken to mitigate its threat, substantial loss of life and property could materialize sooner or later. Xu et al. [23] described such a tragedy with about 100 casualties that occurred on August 13 and 14, 2010. Multiple debris flows occurred during rain storms in this period, including those at Wenjia and Zoumaling gullies, Hongchun gully and Longchi. Figure 7a shows the natural topography in Yinxiu vicinity prior to Wenchuan earthquake, while Figures 7b and 7c show the same area after the 2008 earthquake and 2010 rain storms, respectively.



(a) Original intact topography in image taken on March 31, 2006 (before earthquake)

(b) Widespread landslides in airphoto taken on May 18, 2008 (after earthquake)

(c) Multiple debris-flow fans in airphoto taken on August 15, 2010 (after rainstorms)

Fig. 7 - Yinxiu Debris-Flow Events after Rainstorms on August 13 and 14, 2010
(http://www.itc.nl/pdf/newsevents/landslides/tang_chuan_presentation.pdf)

3.2.2 Persistent Radiation after Tohoku Earthquake

More than five years have passed since the 2011 magnitude 9 Tohoku-Oki, earthquake. Radiation-contaminated groundwater has continued to enter the Pacific Ocean at the damaged Fukushima Daiichi nuclear power plant. In turn, radiation-contaminated sea water, albeit at much lower concentration, has been detected along the west coast of North America. Figure 8a shows the plant site on Google Earth on May 31, 2015, while Figure 8b shows the schematic scheme of the TEPCO seaside impermeable wall and subdrain operations to intercept radioactive groundwater for treatment before release [24]. Small circles shown on Fig. 8a are storage tanks for storing contaminated radioactive groundwater.

Fig. 8(a) - Plant Site on Google Earth (May 31, 2015)

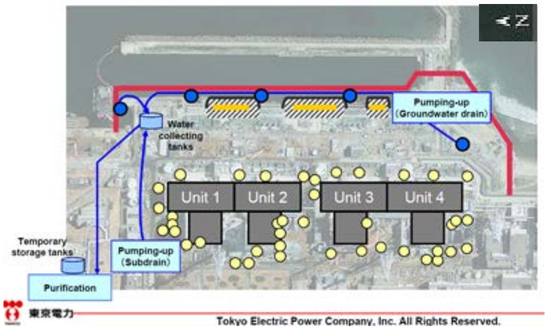


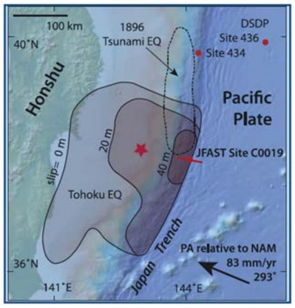
Fig. 8(b) - Schematic scheme for intercepting radioactive groundwater (TEPCO 2015)

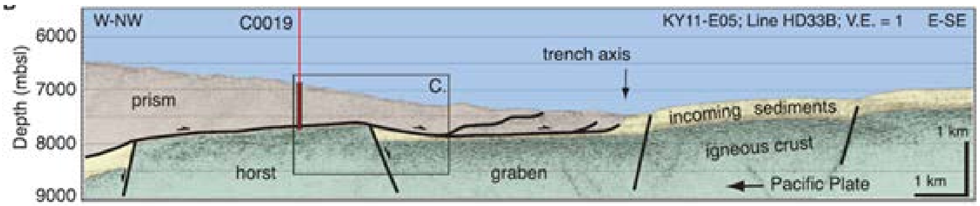
4. Drilling Investigation of Seismogenic Faults

Post-earthquake investigation after the Wenchuan and Tohoku earthquakes included difficult and costly drilling investigation of the causative faults:

4.1 Longmenshan Fault - Li et al. [25] reviewed deep hole (WFSD-1 and WFSD-2) drilling results and records of fault-zone trapped seismic waves obtained from a cross-fault linear-array aftershocks survey as well as those obtained from network stations for the Yingxiu-Beichuan fault (see Fig. 4). The principle fault slip was intercepted at 589 m and 1230 m depth, respectively at the two holes, with a distinct low-velocity, damaged rock zone at seismogenic depths. The seismic velocity within this damaged zone was found to be reduced ~10% by the mainshock from comparisons of seismic wave records obtained prior to and after the main event.

4.2 Japan Trench Fault - The Japan Trench Fast Drilling Project (JFAST) drill site, C0019, is located atop a horst about 200 km offshore of Sendai city, seaward of the 2011 earthquake hypocenter and landward of the Japan Trench (see Fig. 9). A multi-channel seismic survey was first carried out at the drill site to assist locating the top of the basalt of the subducting plate as the strong seismic reflectors. Three closely-spaced holes (>844 m depth) were drilled in the spring/summer of 2012 beneath the seafloor about 7000 m below sea level, employing the drilling vessel Chikyu. The first hole was logged using natural gamma ray and multiple resistivity sensors, and the second hole was core-sampled at key horizons. A tubing containing a string of high-precision temperature sensors was then lowered in the third hole for temperature monitoring over a period of 9 months from August 2012 to April 2013. It is inferred that about 40 m to 50 m co-seismic fault-slip deformation was localized within a limited thickness (less than 5 m) of smectite clay [26]. The monitored temperature data indicates a 0.31°C temperature anomaly at the plate-boundary fault due to heat generated by frictional forces with an apparent friction coefficient of 0.08 during the earthquake [27]. Laboratory tests, using a rotary shear apparatus capable of shearing at a high velocity, were carried out on the retrieved smectite clay samples at stress and shear-rate conditions comparable to the in situ conditions during the earthquake under both drained and undrained condition. Test results corroborate with co-seismic shear behaviour of the fault at a shallow depth near the Japan Trench.





(a) Location of Drill Site C0019 (b) Cross Section at Drill Site Showing Geologic Structural Setting

Fig. 9 - Location and Geologic Structural Setting of JFAST C-0019 Drill Site (Chester et al. 2013)

5. Evolution of Societal Response to Earthquake/Tsunami

National response strategy to seismic hazard varies with the nation's technological development, wealth and socio-economic-political system. Progress is being made incrementally in earthquake forecast ranging from long to intermediate and/or short term as well as real-time earthquake and tsunami warning. All stakeholders including government agencies, research institutes and the public have major interest in developing a healthy mechanism to apply the advancement of our knowledge base to improve the societal response to the occurrence of a destructive seismic event. After all, earthquake is a natural hazard which presents a deadly threat to the normal life of human society individually as well as collectively. We need to constantly improve our ability to cope with its threat, minimize its damage, and restore the society in the inflicted regions to a better state more resilient to its next assault. Outlined below are some noteworthy developments.

5.1 Earthquake and Tsunami Forecast/Prediction and Warning

Presently, our long to intermediate term forecast capability seems to serve our general needs to an acceptable degree with the exception of some underestimated cases (eg. Sumatra, Indonesia; Wenchuan, China and Tohoku, Japan) as well as those cases where institution build-up is needed to improve the local practice (eg. Haiti).

In general, short term earthquake forecast refers to the specification of the time, location, and magnitude of future earthquakes within stated confidence limits but with sufficient precision that a warning can be issued. In practice, it is preceded by the long and intermediate term forecast. It is fair to say that the short-term forecast remains to be both a difficult and hotly debated topics fraught with many pitfalls. On one hand it could contribute enormously in reducing life loss and injury in the impacted area, when the correct forecast is made. However, conversely, confusion, chaos and economic loss would ensue, especially for a highly developed society, if the forecast fails. Perhaps the way out of this dilemma is not to evaluate the success of a forecast with too high a standard on its precision. The nucleation or triggering process of earthquake is an evolving one, that requiring painstaking effort to follow its development during the critical final phase. Due to our limited understanding of this process at the present, demanding too high a precision could be counter-productive and discourage the pursuit of this scientific challenge. Recent advancements, such as observations of two sequences of slow-slip transients propagating towards the initial rupture point [28] and precursory crustal movements [29] before the 2011 main shock of Tohoku EQ, offer renewed encouragement for this pursuit.

The success of a forecast could be evaluated by its scientific basis, as well as its practical value in reducing life loss and injury during the actual event. In this context, it is probably helpful to consider the successful case of the 1975 Haicheng earthquake forecast [30] and the tragic case of heavy casualty suffered in the 1976 Tangshan earthquake [31]. The presence of a foreshock in the former and its absence in the latter appeared to be an important factor for the contrast between the two events. However, even during the tragic Tangshan event with a total fatality close to a quarter of million, the county of Qinglong, about 120 km from the epicentre with a population of 470,000, suffered 7,300 collapsed and 180,000 damaged houses but only one fatality. This county-wide success among a regional tragedy was credited to the actions of local decision makers. The Qinglong inhabitants were, in fact, in an earthquake alert program starting from three days prior to the main shock based on general seismic forecast information available at the time [31]. Thus, the actions of decision makers did play an important role in the success of executing an earthquake-impact mitigation operation based on forecast. Li and Yang [32] cited two other successful forecast events in China: magnitude 7.3 and 7.4 Longling, Yunnan earthquakes on May 29, 1976 and two magnitude 7.2 Songpan-Pinwu, Sichuan earthquakes on August 16 and 23, 1976. It is worth to note that all these successful events occurred in 1974 to 1976. It might have something to do with the zeitgeist of that period, as well as heavy involvement of the public, both in watching for earthquake precursory anomalies and in taking preventive and harm-reduction actions.

5.2 Manslaughter Court Case Evolved from 2009 magnitude 6.3 L'Aquila, Italy earthquake

Destroyed by earthquakes in 1461 and 1703, L'Aquila in Italy was rebuilt and had a population of about 73,000 in 2009. Since October 2008, earthquake tremors had unnerved the local population. The "prediction" of a pending large earthquake, issued by Mr. Gioacchino Giuliani, an amateur seismologist and technician at Italy's National Institute of Nuclear Physics, seemed to have further heightened the public anxiety level. On March 31, 2009, the National Commission for Prediction and Prevention of Major Risks convened in L'Aquila to assess the earthquake swarm, and held a press conference. According to the minutes, Mr. Enzo Boschi, President of the National Institute of Geophysics and Volcanology indicated that "it is unlikely that an earthquake like the one in 1703 could occur in the short term, but the possibility cannot be totally excluded." During a media interview prior to the meeting, Mr. Bernardo De Bernardinis, then deputy chief of Italy's Civil Protection Department, who might have been influenced by the desire to dispel the public alarm caused by Mr. Giuliani's "prediction" of a large earthquake, conveyed a somewhat reassuring opinion [33].

On April 6, 2009, a magnitude 6.3 earthquake hit L'Aquila and its vicinity, killing more than 300 people and injuring more than 1,500. The quake destroyed about 20,000 buildings and displaced 65,000 people. In 2010, an indictment was made against Mr. Bernardo De Bernardinis and six other earthquake scientists, charging them with manslaughter and negligence for failing to warn the public of the impending risk. The seven defendants were convicted of manslaughter in 2012 and each received a six-year jail sentence. The court case went through two levels of appeals and reached the Italy Supreme Court. In November 2015, the Supreme Court acquitted the six scientists, but kept a reduced two-year sentence on "suspension" for Mr. De Bernardinis.

This episode illustrated how complex the interplay of the respective roles among stakeholders could become, when facing a potential impending seismic hazard with increasing seismic activities lurching in the background.

6. Conclusions

Five main conclusions are summarized below:

1. The single-minded pursuit of population densification in vulnerable urban centres needs to be countered by due consideration of its sustainability in light of inescapable natural hazard including seismic events. Improvement of local design and construction practice in developing regions should cover both engineered and non-engineered structures. Government assistance in building economical and seismic-resistant model structures could enhance local engineering standard. Every opportunity in improving seismic capacity of local building stocks such as urban renewal or redevelopment project should not be wasted.
2. In general, current seismic hazard assessment practice provides a rational means in determining the seismic demand at a given region. However, recent events do seem to suggest that the likelihood of the largest credible event that may actually occur is often either underestimated or discounted without justification. This weakness has many causes: such as sub-standard practice in developing areas, eg. in Haiti, and limitation of seismic database or in-depth research, such as in Longmenshan in China and Tohoku in Japan. To counter this underestimating tendency, one could apply seismic database and understanding in other areas or time windows to regions of similar seismo-tectonic setting. Satake's et al. [34] confirmation of 1700 Cascadia earthquake along the northwest coast of North America in Japanese tsunami records, Zhang's [12] warning about potential threat of slowly slipping faults, and Kagan and Jackson's [19] application of moment conservation principle are such examples.
3. Traditional and compounded secondary earthquake impact deserves close scrutiny, especially with respect to its influence on various failure modes of critical facilities, such as nuclear, chemical, hazardous-material operation and storage facilities, reservoir, landslide lake and mine tailings impoundment. Decision makers need to take to heart the tragic lessons we learned from underestimated real hazards, and give due deliberation on the impact of a seismic event of relatively low probability yet with extremely destructive potential. Depending on the consequence of facility failure, selection of maximum credible (considered) seismic event as design scenario could well be a prudent choice.
4. Post-earthquake investigations including drilling and coring of fault-slip zone after both Wenchuan and Tohoku events have contributed to better understanding of what is happening at the causative faults. Preliminary results suggest that fault slip occurs in the wet clay gouge zone with low steady-state friction coefficient involving heat generation by friction between two moving planes. Although many huddles remain ahead, there seems to be some recent encouragements in the thorny issue of short-term earthquake forecast such as successful prevention of casualties at Haicheng and Qinglong in China and presence of precursors before the Tohoku earthquake in Japan. To reap positive benefit of this difficult

pursuit, technical advancement in understanding the final stage of earthquake nucleation process and its associated phenomena is critically important.

5. Since the last quarter of the 20th century, earthquake forecasting has been practiced in one form or another in different countries such as China, Japan, USA and Italy with limited success. Even though variegated problems surfaced during this period of initial trials, one could consider these problems, some psychological and others economical and sociological, as growing pains. We should learn collectively from the limited successful cases as well as numerous failures and mistakes since 1970s. As our capability in this endeavour improves with further scientific advancement, we may improve incrementally our ability to mitigate earthquake impact with additional insights on the seemingly unfathomable process of the final approach of a major earthquake.

   The L'Aquila EQ and 2005 Katrina hurricane impact on New Orleans, USA showed us the complex dimensions of emergency preparedness and response to a natural disaster. A truly successful case of an earthquake forecast is represented by how much loss reduction it contributes to. A close and healthy working relation among authorized forecaster, emergency responders, media and public is a necessary start.

As we move forward in the 21st century, the pace of civilization development will no doubt accelerate. The societal response to earthquake will evolve by learning from the experience of each major event around the world. The issues discussed herein need to be addressed with the objective of finding practical means to applying our earthquake know-how to mitigate its impact in terms of life loss and injury as well as economic and environmental loss.

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