Some Recent Developments of Post-Earthquake Restoration and Pre-Earthquake Preparation

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ABSTRACT:

Considerable challenging works have been accomplished, and improvements upon earthquake preparedness have been made during the period in between those when the world is preoccupied by the sensational reports of major seismic disasters by the mass media. This paper first reviews the following developments in post-earthquake restoration and adaptation:

- restoration and subsequent completion in 2007 of the Bolu tunnels and viaducts located in the North Anatolian active fault region in Turkey, which were damaged during construction by the 1999 magnitude 7.1 Düzce earthquake;
- adaptation with earthquake and landslide potential in the aftermath of the 2001 magnitude 7.6 and 6.5 earthquakes of El Salvador;
- development of Indian Ocean Tsunami Warning System after the enormous casualties caused by the “stealth” tsunami induced by the 2004 magnitude 9.1 Sumatra earthquake; and
- reconstruction and resettlement after the 2008 magnitude 7.9 Wenchuan earthquake in China.

It then turns to the ongoing effort to mitigate the impact of a Cascadia subduction earthquake with a potential maximum magnitude of 9 on liquid-fuel supply chain for Oregon, along a 13 km stretch of the lower Willamette River in Portland, Oregon, USA. Finally, it discusses two recent seismic-related developments to highlight that earthquakes can have unexpected, secondary yet vital impacts on the general public:

- meltdown of fuel rods at Fukushima Dai-Ichi nuclear power plant and its ongoing radiation release after the March 11, 2011 magnitude 9 Tohoku-Oki earthquake-tsunami event in Japan, and subsequent shutdown of undamaged nuclear power plants that have led to ongoing electricity shortage in Japan, and worldwide reassessment of the nuclear power industry; and
- recent trial in the L’Aquila Court, Italy of seven scientists and experts on manslaughter charges for allegedly failing to sufficiently warn residents, before the 2009 magnitude 6.3 L’Aquila earthquake that killed more than 300 people in central Italy.

Keywords: post-earthquake restoration, earthquake preparedness, secondary earthquake impact.

1. INTRODUCTION

As long-time members of the Earthquake Investigation Committee (EIC) of American Society of Civil Engineers Technical Council on Lifelines Earthquake Engineering (TCLEE), the authors have tracked the post-earthquake developments for some of the events that they were involved. This paper synthesizes some of the restoration achievements and earthquake preparedness efforts as well as recent cases that have broad and profound socio-economic ramifications involving the following past and potential seismic events:

- 1999 M 7.1 Düzce, Turkey earthquake;
- 2001 M 7.6 and 6.5 El Salvador earthquakes;
- 2004 M 9.1 Sumatra, Indonesia earthquake;
- 2008 M 7.9 Wenchuan, China earthquake;

- Cascadia M~9 potential subduction earthquake along the northwest coastline of U.S.A and Canada;
- 2009 M 6.3 L'Aquila, Italy earthquake; and
- 2011 M 9 Tohoku-Oki, Japan earthquake.

2. POST-EARTHQUAKE RESTORATION AND ADAPTATION

2.1. Restoration of Bolu Tunnels and Viaducts in Turkey - since November 12, 1999 M 7.1 Düzce earthquake

2.1.1. Bolu Tunnels

Mount Bolu Tunnels are 2.9 km long twin highway tunnels through the Bolu Mountain between Kaynasli and Yumrukaya. The tunnels are part of the O-4 E80 Trans-European Motorway. The main challenge during tunnel construction was the encounter of several minor faults parallel to the North Anatolian Fault. Shear zones include 200 m to 300 m thick bands of highly plastic clay fault gouge sandwiched between a metamorphosed limestone and marble formation. Atterberg limits of a gouge sample showed a liquid limit of 100%, plastic limit of 29% and water content of 22%. Total convergence of the tunnel in the gouge zone reached up to 1 m, far exceeding the acceptance criteria of 200 mm. During the Düzce earthquake, both tunnels collapsed 300 m from the eastern portal, where the unreinforced concrete lining was not yet placed in the fault gouge zone (GEER 1999). Following the earthquake, two active faults were recognized along the tunnel alignment as seen on Fig. 1. Because of the large tunnel section and already defined excavation geometry, the articulated tunnel design as illustrated on Fig. 2 was adopted for the tunnel through the Bakacak Fault. This approach utilized independent tunnel segments over the length spanning beyond the fault rupture zone, and allowed the concentration of fault movement at joints linking the segments. The joints were specially designed to prevent soil squeezing between the segments and to bridge the static soil pressure, but at the same time offering low resistance to seismic deformation. The ratio of the length to the width of each tunnel segment was kept about 1/3. Option 4 segment cross section as shown on Fig. 3 was selected for crossing the Bakacak Fault, with two smaller circular Bench Pilot Tunnels of 5.6 m diameter driven ahead of the crown excavation (Russo et al. 2002).

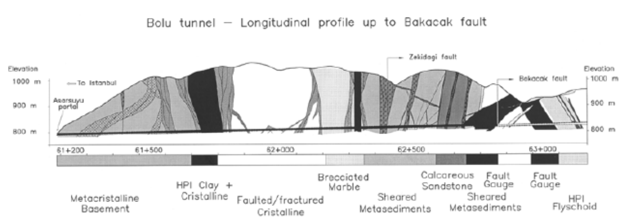

Figure 1. Zekidagi and Bakacak Active Faults Along Tunnel Profile (Russo et al. 2002)

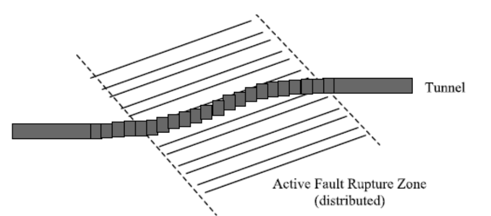

Figure 2. Articulated Tunnel Design to Distribute Shear Deformation across Fault Rupture (Russo et al. 2002)

2.1.2. Bolu Viaducts

The 2.3 km long, dual-structure West Bolu Viaduct (see Fig. 4) was near completion when the Düzce earthquake occurred. The viaduct has 59 spans, and its 40 m long spans consist of 7 lines of simply-supported, pre-stressed concrete V-shaped box girders seated on pot bearings with stainless steel passive energy dissipation units. The top portion of the device is a crescent-moon-shaped yielding element to provide two-dimensional energy dissipation over a 32-cm range of horizontal motion. The unit is connected to the base by a pair of piston dampers (see Fig. 5). The deck slab is continuous over 10 spans. A piston and a sliding unit were incorporated in the energy dissipation unit at the expansion joints and at the centre pier of each 10-span deck segment. The piers are single, octagonal hollow-core reinforced concrete columns, which are 8 by 4.5 m in section and varying in height from 10 to 49 m. The piers are founded on reinforced concrete footings, which are supported in turn by twelve 1.8-m diameter cast-in-drilled-hole piles through surficial soils down to the bearing stratum of alluvial layer at a depth of about 30 m. The viaduct already suffered the following relatively minor damages during the August 17, 1999 distant Kocaeli earthquake:

- relative displacement of the deck to bent cap up to 8 cm longitudinally and 6 cm transversely including 1 cm plastic deformation of the damper; and
- concrete spalling at an expansion joint.

During the November 12, 1999 Düzce earthquake, the viaduct suffered the following additional severe damages (GEER 1999):

- the longitudinal deck movement exceeded the design limits with many of the metal plates of the deck support falling down, and some of the deck beams were supported on the pier for only a few inches;
- a pier rotated 12 degree as the result of horizontal differential ground motion across the fault rupture; and
- further damages to the special damper devices.

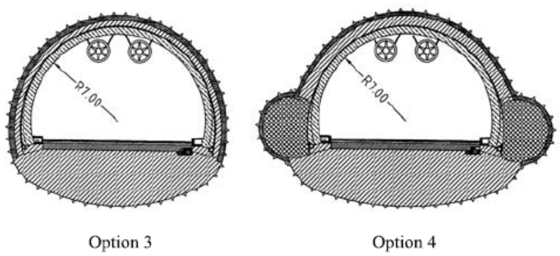

Figure 3. Segment Options of Tunnel Cross Section (Amberg and Russo 2001)

Figure 4. General View of West Bolu Viaducts (Ghasemi 2004)

The viaduct retrofit involved the following:

- replacing the initial damping device shown on Fig. 5 by the friction pendulum device shown on Fig. 6, which was judged to be able to accommodate a large permanent fault rupture offset without damaging the isolation unit and the viaduct as well as capable of dissipating large amounts of energy;
- repositioning the deck slab for an entire 10-span segment at a time; and
- including additional piles and extending existing footings to repair damaged footings near the fault rupture.

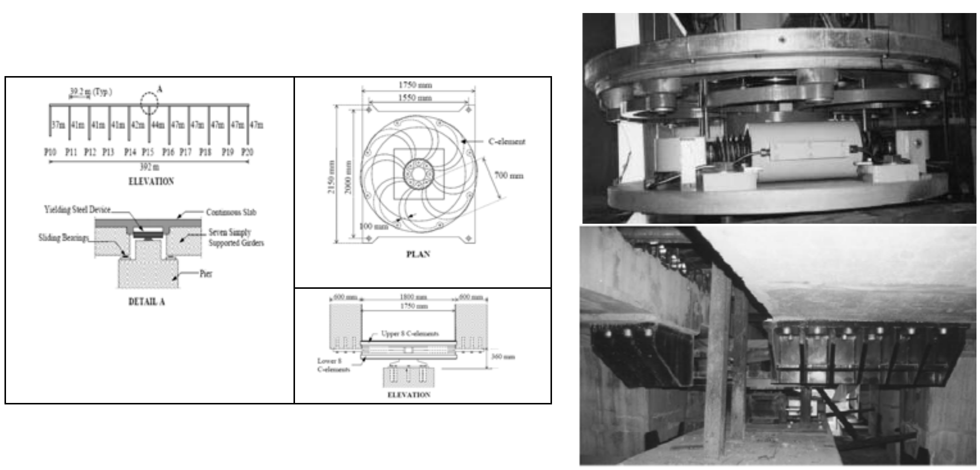

Figure 5. Passive Energy Damping Devices Incorporated in West Bolu Viaducts (GEER 1999 and Roussis et al. 2003)

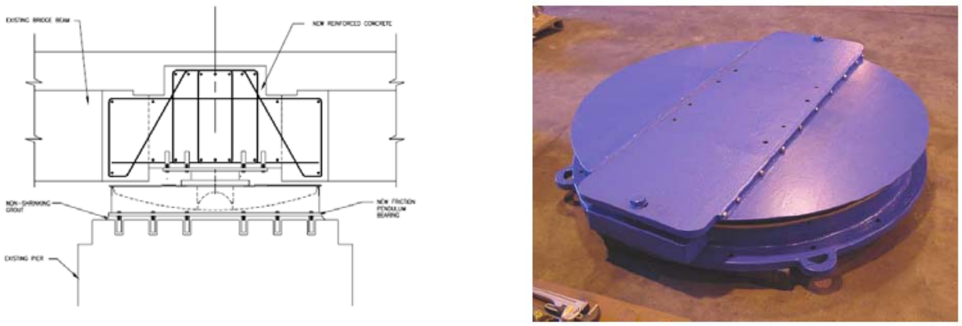

Figure 6. Retrofit Scheme at Typical Interior Pier Using Friction Pendulum Isolation Bearing (Ghasemi 2004)

2.2. Adaptation to Earthquake and Landslide Potential in El Salvador - since 2001 M 7.6 and 6.5 El Salvador earthquakes

The geological setting of El Salvador is rather young. About one quarter of the bedrock surface in the country is Pleistocene in age, while the remainder is covered by Tertiary rock, mainly belonging to Pliocene epoch. Water and lava are also agents that rework the weathered bedrock or surficial soil to form sedimentary deposits. There are three seismic sources: intra-slab earthquakes within the subducting Cocos Plate, crustal earthquakes within the upper plates and inter-plate subduction earthquakes. The region is also subject to heavy storms. Thus, strong ground motions and high water table during raining season make the area vulnerable to numerous and sizable landslides in mountainous terrain, and liquefaction/ lateral spreading in lowlands (Lomnitz and Elizarraras 2011).

To cope with the seismic threat to population, traditional adobe and bahareque (supported by mud-filled wooden lattice or timber skeleton) houses are discouraged, improved adobe construction method (Blondet et al. 2003) and reinforced masonry house (Calvo et al. 2010, see Fig. 7) are adopted. In addition, grass-root community efforts have been mobilized to improve the public awareness of natural hazards as well as the self-help means to protect themselves. Figure 8 shows that gabion structures have been used effectively to protect the geothermal wells against rock fall, mud-flow and landslides.

Figure 7. Reinforced Masonry Building to Improve Seismic Resistance (Calvo et al. 2010)

Figure 8. Gabion Walls Constructed to Protect Geothermal Wells (Barrios et al. 2011)

The Las Colinas landslide occurred in pyroclastics of the Cordillera del Básalmo. It killed more than 600 people and destroyed about 200 homes in a residential area. Konagai et al. (2002) made a comprehensive investigation of the slide and provided a better understanding of the slide mechanism. Figure 9 shows the topography in the vicinity of the slide and the crack pattern along the top edge of the slide. Figure 10 shows the shear versus normal stress and shear resistance versus shear displacement relations obtained from two undrained ring shear tests (Sassa 1996) on pumice specimens (one with the degree of saturation Sr=81% and the other fully saturated). While the peak strength of the saturated sample is 71% of that of the unsaturated one, the residual strength of the saturated sample is only 25% of its counterpart of the unsaturated sample. Thus, once earthquake loading induced shear displacement in the saturated material beyond its peak strength, the drastic reduction of its shear strength would precipitate rapid failure of the sliding mass, and trigger a flow slide. To prevent similar tragedy from recurrence, a buffer zone with an adequate distance from the toe of the slope should be created, and no housing development should be permitted within the zone. This would require considerable effort in microzonation to delineate landslide susceptible zones based on geological and geotechnical investigations.

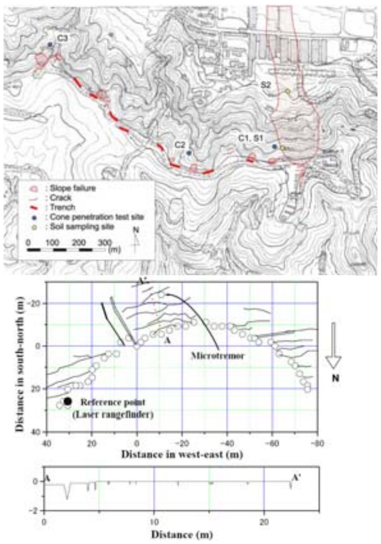

Figure 9. Topography in the Vicinity of the Las Colinas Slide and Crack Pattern along Top Edge of the Slide (Konagai et al. 2002)

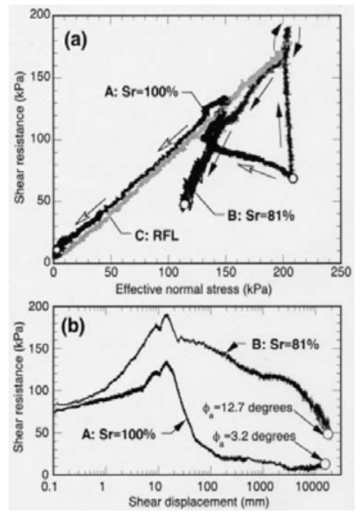

Figure 10. Shear versus Normal Stress and Shear Resistance versus Shear Displacement Relations Obtained from Undrained Ring Shear Tests (Konagai et al. 2002)

2.3. Built-up of Tsunami Warning System around Indian Ocean - since Sumatra M 9.1 earthquake in 2004

The unanticipated heavy casualty in the order of 230,000 people around the Indian Ocean caused by the December 26, 2004 earthquake-tsunami event prompted the creation of a tsunami warning system for the Indian Ocean, emulating the established Pacific warning system based in Hawaii for the Pacific Ocean. It was initiated in a United Nations conference held in January 2005 in Kobe, Japan (UNESCO 2006). The system consists of 25 seismographic stations and three Deep-ocean Assessment and Reporting of Tsunamis (DART) sensors, relaying information to 26 national tsunami information centers. It became active in late June 2006, following the leadership of UNESCO. The system has been operated by Japan and Hawaii, USA, and gone through a full scale test on October 12, 2011. Its continual operation is expected to be turned over to regional centres in 2012. UNESCO-Intergovernmental Oceanographic Commission (IOC) also seeks to establish warning systems in the North East Atlantic, Mediterranean and adjoining seas, and the Caribbean. Protection is also being reinforced in the South West Pacific and the South China Sea. However, UNESCO warned that further coordination among governments and methods of relaying information from the information centers to the civilians at risk are required to make the system truly effective. On the other hand, wide spread use of internet, blogs and social networks could potentially be harnessed as an effective, informal means to spread tsunami warning, especially to distant coastal areas, to reduce casualties.

In the immediate aftermath of the July 17, 2006 Java earthquake, the Indonesian government received tsunami warnings from the Hawaii center and the Japan Meteorological Agency, but failed to relay the alert to its coastal citizens. However, at least 23,000 people did evacuate the coast after the quake, due to fear of tsunami and destroyed homes. Suggestions were made to make use of the loudspeakers fitted to mosques for broadcasting tsunami warnings. For the April 11, 2012 magnitude 8.6 earthquake in Sumatra, tsunami alerts were issued across the Indian Ocean, and were later lifted. However, because the quake was a strike-slip event with little vertical sea floor movement, only small tsunami waves up to about 1 m were reported. German researchers in German Research Centre for Geosciences (GFZ) in Potsdam recently indicated that by employing Global Position System (GPS), they could provide tsunami alert in 3 to 4 minutes.

2.4. Reconstruction and Resettlement of Beichuan in China - after 2008 M 7.9 Wenchuan earthquake

The unique Chinese mechanism for emergency response, recovery and reconstruction involved communities and jurisdictions located far away from the damaged areas. This twinning of communities in need and those offering helping hands accomplished the dual goals of sharing enormous financial hardship, and cultivating camaraderie among population. Immediately after the earthquake, temporary dwelling units were set up across the earthquake damaged region. Figure 11 shows one community thus set up to facilitate residents to resume normal life.

Figure 11. Temporary residential units and Leigu Middle School /Health Clinic Lined on Either Side of a Concrete-Paved Road (ESS 2008).

A comprehensive three-year reconstruction program covered the management organization and socio-economical structure for regional revitalization, and was carried out by the twinned communities. Figure 12 shows a new Beichuan town bearing considerable ethnic Qiang characteristics, constructed in Yongchang City to avoid geological hazards including massive landslides that destroyed the old town located about 25 km further upstream. A national earthquake museum was set up at the old town site with a memorial hall. Figure 13 shows rebuilt houses in Yingxiu town in the epicentral region. During the fast-track reconstruction program, the government had to overcome the bottle-neck problem of resource shortage and supply disruption.

Figure 12. A Birds'-eye view of New Beichuan Town in Jongchang City (xinhua english.news.cn Vol. 59, No. 12, Dec, 2010)

Figure 13. Rebuilt Houses in Yingxiu Town (xinhua english.news.cn 2010-9-27)

3. PRE-EARTHQUAKE PREPARATION AT MARINE OIL TERMINALS, PORTLAND, OREGON, U.S.A

Five petroleum companies operate the marine oil terminals in Portland, Oregon, USA, and receive the majority of the fuel for the state of Oregon. The ships and barges enter through the river mouth at Columbia Bar by the Pacific Ocean, travel about 160 km up the Columbia River and deliver liquid fuel to the marine oil terminals located on a 13-km stretch of the lower Willamette River, 7 km upstream of its confluence with the Columbia River. All the terminals are underlain by naturally deposited river sediments from the Willamette River and landfill placed to extend developable land.

The seismic vulnerability of the marine oil terminals and the transportation route from the terminals to the Columbia Bar against a magnitude 9 Cascadia subduction earthquake was evaluated (Wang 2008). The evaluation was based on the conditions of the existing infrastructures, knowledge about similar structures obtained from investigation of past earthquakes elsewhere, and geotechnical engineering analyses. The purpose of this work was to better appreciate the reliability of the liquid-fuel supply chain for Oregon. The following outlines work performed to date.

3.1. Marine Terminals

The 5-m thick, loose sandy soils that support the foundations of the wooden piers are susceptible to liquefaction and lateral spreading. The epicentral distance could be as close as 80 kms depending on the actual rupture location, and the expected peak horizontal ground acceleration would be about 0.25 g and the ground motion lasting for 80 seconds. Fast Lagrangian Analysis of Continua (FLAC) computer program (Itasca 2005) was used to evaluate ground deformation by Steven Bartlett, University of Utah and author Yumei Wang. Five earthquake time histories appropriate to the site were selected, and input parameters were estimated based on subsurface information obtained from local soil borings. The results from the FLAC analyses are compared with those obtained by Youd et al. (2002) method on Figure 14. The figure indicates that the lateral translation of the ground at a 2% slope could reach 5 m.

Figure 15 shows three oil terminal piers, with a ship and a barge berthed at either side of the middle pier. Figure 16a shows one of the piers at the water’s edge with a timber "wall" that would likely concentrate seismic stresses and lead to failure of the pier. Figure 16b shows a poorly maintained post with inadequate element connection. All three piers would likely experience extended damage due to a combination of lateral spreading and major structural deficiencies.

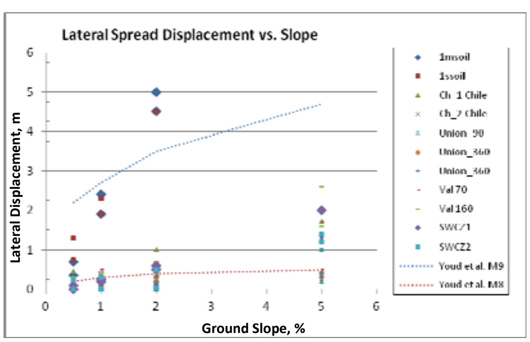

Figure 14. Results from FLAC deformation analyses as compared with those by Youd et al. (2002) method.

Figure 15. Marine oil terminals in Portland, Oregon, USA.

Figure 16. (a) Side view of pier and its foundation (b) Close-up of a wooden post on spalled concrete post.

3.2. Shipping Channel

The shipping channel is vulnerable to closure due to the following four potential failure modes:

- tsunami scour and debris blockage near the mouth of the Columbia River;
- underwater slope failure along steep banks of the navigable river channel;
- collapse of overhead structures from earthquake shaking; and
- broken buried pipelines at river crossings.

The structures that may collapse or fail and block the waterway include the 1966 Astoria-Megler bridge (Fig. 17), 1930 Lewis and Clark bridge in Longview, Washington, 1931 St Johns bridge, 1908 BNSF rail bridge, multiple high-voltage electrical transmission-line crossings (Fig. 18), and several 1960s-vintage buried natural gas and liquid-fuel pipelines. The closed channel has to be cleared and restored by the U.S. Coast Guard before resumption of navigation.

Figure 17. The 1966 Astoria Megler Bridge that spans the Columbia River. The approach segment in the foreground has major structural deficiencies

Figure 18. The high-voltage electrical transmission-Line crossings founded on subsoil susceptible to liquefaction and lateral spreading

4. RECENT SEISMIC-TRIGGERED DEVELOPMENTS

The following two recent earthquake-related developments have the potential of having profound impacts well beyond the traditional borders of earthquake disasters:

- Legal Aftermath of the April 6, 2009 L'Aquila, Italy Earthquake; and
- Nuclear Meltdown after the March 11, 2011 Tohoku-Oki Earthquake-Tsunami in Japan.

The former could affect the conduct of professionals involved in issues concerning public safety, while the latter curtails Japanese operation of nuclear power plants, and triggers reassessment of nuclear power industry in countries around the world.

4.1. Legal Aftermath after the 2009 L'Aquila Earthquake in Italy

L'Aquila, Italy, destroyed by earthquakes in 1461 and 1703, was rebuilt and had a population of about 73,000 in 2009. Since October 2008, earthquake tremors have unnerved the local population. The "prediction" of a pending large earthquake issued by Gioacchino Giuliani, an amateur seismologist and technician at Italy's National Institute of Nuclear Physics, seemed to have further raised 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, 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 the press conference, Bernardo De Bernardinis, then deputy chief of Italy's Civil Protection Department, might have been influenced by the desire to dispel the public alarm caused by Giuliani's "prediction" of a large earthquake and conveyed a reassuring opinion (Pielke 2011).

Unfortunately 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. Figure 19 showed the visit of L'Aquila by EU commission Chief Barroso three months later during the G8 summit meeting. A contribution of 470 million Euros and other post-earthquake initiatives were also made.

In 2010, an indictment was made against 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 court case is currently continuing with ongoing debates among scientists and the public at large. At stake are issues of the public safety, and communication on risk of rare events of low probability but high consequences (Cohen 2012). The outcome of the case could have far-reaching effect on the conduct of professionals working in the field of hazard reduction, emergency response and public safety.

4.2. Nuclear Meltdown at Fukushima Dai-ichi Power Plant after the 2011 Tohoku-Oki earthquake-tsunami in Japan

The destructive power of earthquake and tsunami has long been experienced and recognized by the human race since its existence. However, the March 11, 2011 magnitude 9 Tohoku-Oki earthquake has revealed another relatively modern threat, i.e., the triggering of a long-lasting and potentially deadly nuclear incident. At the Fukushima Dai-Ichi nuclear generating station (see Fig. 20), the disruption of the cooling systems of nuclear reactors and power failure resulted in the meltdown of reactor fuel rods.

It was reported that during risk assessment of the nuclear power station prior to the earthquake, a tsunami expert was overruled by an executive, when the survivability of the reactors in a potential tsunami event was raised. Thus, the design flaw at this plant was not corrected, while another plant with a newer design survived the current event without problem. Construction records also revealed that in 1967, the owner, Tokyo Electric Power, excavated 25 m off the 35 m high natural ground where the reactors were to be located. The lowering of the site grade appeared to facilitate equipment transportation as well as pumping of seawater for cooling the reactors.

The current solution is to abandon the power station, and to eventually entomb the damaged reactors in concrete after their cool-down, even though ongoing radiation leak continues to contaminate the plant site, its surrounding land and sea thirteen months after the earthquake (April 2012). It is uncertain how long will it take to bring the radiation problem at the Fukushima Dai-Ichi plant site under control.

The Onagawa nuclear power plant located 120 km northeast of Fukushima Dai-Ichi, on the other hand, fared much better, because of the foresight of the operator, Tohoku Power Electric Co, to build the plant out of the reach of tsunami, and the fact that the remaining functional external power line out of the original five helped to bring the three nuclear reactors into cold shutdown in 10 hours. Nevertheless, the plant suffered turbine fire on March 11, 2011, elevated radiation level to 21 μSv/hour for 10 minutes on March 13, 2011 and leak of radioactive water because of a magnitude 7.1 aftershock on April 7, 2011.

Currently only one of the 54 Japanese nuclear power plants, that were in service prior to the March 11, 2011 earthquake, is operating as of April 2012, because of safety check in response to local concerns. This active reactor, Hokkaido Electric Power's 912-MW Tomari No. 3 unit, is also set to be shut down on May 5 for maintenance. The Japanese government is racing to get two idled nuclear reactors, the No. 3 and No. 4 reactors at Kansai Electric Power Co's Ohi plant in Fukui, western Japan, running again by May 2012 to avoid a total shutdown of nuclear power plants. In the meantime, a potentially active fault was recently found right underneath the No. 1 and No. 2 reactors at the Tsuruga plant by the Nuclear and Industrial Safety Agency (NISA).

Germany and Switzerland have indicated their plan to phase out nuclear power plants, while other countries have also started the reassessment of their future nuclear-power development plans. Thus, the radiation concern for all nuclear power plants has to be carefully evaluated, and robust defence measures against natural and man-made hazards have to be implemented around the world.

Figure 19. EU commission chief Barroso visited L'Aquila (http://www.cafebabel.co.uk)

Figure 20. Blast-Damaged Fukushima Dai-Ichi Nuclear Power Plant Unit 3 (left) and Unit 4 (right). (Image: ©Fabio Iuliano, http://pinktentacle.com/)

5. SUMMARY

This paper reviews some of the recent developments related to earthquakes. Examples of accomplished challenging works include: retrofit of Bolu tunnels and viaducts of the O-4 E80 Trans-European Motorway in Turkey, implementation of a new tsunami warning system for the region around the Indian Ocean, and restoration of Beichuan County in Sichuan, China. Ongoing efforts to mitigate potential damages due to future earthquakes include: evaluation for improvement of marine oil terminals in Portland, Oregon, and coping with earthquake and landslide potential in El Salvador. Moreover, new challenges associated with the nuclear energy industry will require the collective wisdom of the human society to strike a delicate balance between its need for clean energy in light of global warming trend and its more fundamental need for a safe environment free from the radiation threat. The implication of the current legal case in Italy will no doubt influence the conduct of professionals working in the field of earthquake engineering and public safety.

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