Earthq Eng & Eng Vib (2014) 13: 141-149 **DOI**:10.1007/s11803-014-0244-y

Earthquake engineering research needs in light of lessons learned from the 2011 Tohoku earthquake

Masayoshi Nakashima[1†], Oren Lavan[1,2‡], Masahiro Kurata[1*] and Yunbiao Luo[1§]

1. *Disaster Prevention Research Institute (DPRI), Kyoto University, Gokasho, Uji, Kyoto, Japan*

2. *Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa, Israel*

Abstract: Earthquake engineering research and development have received much attention since the first half of the twentieth century. This valuable research presented a huge step forward in understanding earthquake hazard mitigation, which resulted in appreciable reduction of the effects of past earthquakes. Nevertheless, the 2011 Tohoku earthquake and the subsequent tsunami resulted in major damage. This paper presents the timeline of earthquake mitigation and recovery, as seen by the authors. Possible research directions where the authors think that many open questions still remain are identified. These are primarily based on the important lessons learned from the 2011 Tohoku earthquake.

Keywords: research needs; earthquake engineering; quick recovery; 2011 Tohoku earthquake

1 Introduction

In the last half a century and more, earthquake engineering research has gained much attention. Indeed, a huge step forward was presented as a result of this valuable research: aseismic design is now an integral part of the design of structures in most seismic zones throughout the world; seismic risk analysis has been introduced and is now commonly used (Cornell, 1968); performance-based design (SEAOC, 1995) and the consideration of serviceability under frequent earthquakes (BCJ, 1981; FEMA, 1997) is now widely accepted; advanced technologies for seismic mitigation in new buildings and for seismic retrofitting of existing ones have been developed and seem to have taken hold in seismic codes and practice (Priestley, 1996; Soong and Dargush, 1997; Kelley and Naeim, 1999; Christopoulos and Filiatrault, 2006); and quantification of seismic recovery of buildings and communities are being sought (Cimellaro *et al*., 2009, 2010; Renschler *et al*., 2010). In turn, this appreciably reduced the effects of past earthquakes. Nevertheless, major damage was still experienced as a consequence of the 2011 Tohoku earthquake and, in particular, due to the subsequent tsunami. Recovery efforts at inundated areas continue more than three years later. Every effort is still being focused on the stability and cleanup operations of the tsunami-damaged Fukushima nuclear plant.

As per AIJ (2012) and references therein, the magnitude 9.0 earthquake produced shaking at the levels of six plus (6+) to seven (7) at a Shindo scale. This scale ranges from zero to seven. Similar to the Modified Mercali scale, the Shindo scale was traditionally associated with visual inspection of damage. Nowadays, however, it is associated with measurements of local acceleration intensities. It is important to note that the size of the rupture causing the 2011 Tohoku earthquake and the size of the subsequent tsunami were not anticipated by the earth science and seismology community as well as by the earthquake engineering community. Nevertheless, historical records indicated that ruptures of this magnitude were experienced about ten centuries ago.

The damage caused by the 2011 Tohoku earthquake is associated mostly with the effect of the subsequent tsunami. Since the fault ruptures were much larger than anticipated, the areas where the maximum run-up height exceeded 30 m extend from Onagawa to Noda, which covers more than 180 km of the Sanriku coast (Mori and Eisner, 2013). Additional effects of the earthquake included subsidence, liquefaction and landslides. Albeit the level of shaking, recent buildings performed reasonably well while the majority of structural damage was experienced by older buildings due to their known deficiencies (NILIM and BRI, 2011; Nakashima *et al*., 2012). Nonstructural damage, on the other hand, was quite significant (AIJ, 2012). This caused major disruption to business and social affairs (AIJ, 2012; Mori and Eisner, 2013).

Correspondence to: Masayoshi Nakashima, Disaster Prevention Research Institute (DPRI), Kyoto University, Gokasho, Uji, Kyoto, Japan
Tel: +81-774-38-4086; Fax: +81-774-38-4334
E-mail: nakashima@archi.kyoto-u.ac.jp
[†]Professor; [‡]Visiting Associate Professor; *Assistant Professor
[§]Post Doctoral Fellow

Received June 16, 2014; **Accepted** July 15, 2014

In addition to nonstructural damage, another major source of disruption is associated with loss of utilities. Loss of electricity, besides the disruption to population, caused major business disruption. This, in turn, has had a huge effect on Japanese industry. In addition to a shortage of electricity, water supply was cut to over one million households while gas supplies were cut for over 400,000 homes immediately after the earthquake. Moreover, breakage of supply chains due to damage to factories, lifelines and means of transport, led to the suspension of business activities.This reveals that the structural and non-structural damage states of individual buildings are indeed important. Nonetheless, its overall performance is strongly governed also by the performance of other entities (AIJ, 2011 and 2012). The overall results of the 2011 Tohoku earthquake manifest the importance of a quick recovery from such an event.

The 2011 Tohoku earthquake was indeed a major one. Nonetheless, stronger earthquakes with epicenters closer to more populated regions are expected to take place in Japan in the not so distant future. Such earthquakes may be associated with the Nankai Trough or inland, next to the Tokyo metropolitan area. In addition, other countries will also experience similar or more damaging earthquakes in the future. Thus, preparedness for such an event and for prompt recovery is required. These necessitate research efforts in related directions.

This paper first presents a timeline of earthquake mitigation and recovery, as seen by the authors. Research needed and related to the stages of earthquake mitigation is then identified. Finally, some conclusions are drawn.

2 Timeline of earthquake mitigation and recovery

The keyword “Resiliency” has been used by many researchers in the context of earthquake engineering and in many ways (see e.g., Bruneau *et al*., 2003; Bruneau and Reinhorn, 2007; Cimellaro *et al*., 2009, and references therein). It is the authors' opinion that the most important aspect of resiliency is the recovery time. Hence, the definition given in Nakashima *et al*. (2012) is adopted here as the ability to recover to normal conditions (or functionality) as quickly as possible. The associated process is described in Fig. 1 by plotting the functionality versus time. It consists of two main stages: Stage I describes the effect of the ground motion and the disruption it causes to normal functionality while Stage II describes the recovery stage.

A quick recovery to normal functionality could efficiently be achieved by minimizing the effect of the ground motion and its disruption to normal functionality (Stage I). This has been the focus of research for many years, and still is. While traditionally damage to structural components was the only design criterion, nowadays, nonstructural damage gains much attention (Reitherman *et al*., 1995; Villaverde, 1997a, 1997b). In addition, many efforts have been made to develop

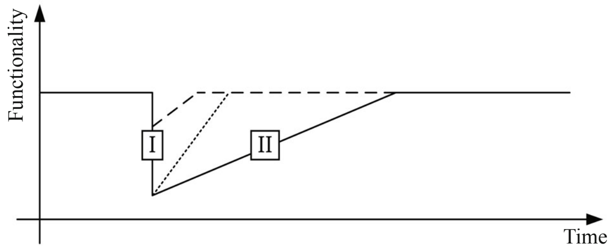

Fig. 1 Functionality versus time

structural systems and technologies to result in “damage free” buildings, or at the least minimize damage. Examples of these are base isolation systems (Skinner *et al*., 1993; Kelly and Naeim, 1999), rocking mechanisms (Priestley, 1996), passive and active control (Soong and Dargush, 1997; Christopoulos and Filiatrault, 2006), and pseudo-negative stiffness semi-active control (Iemura and Pradono, 2002) as well as passive negative stiffness devices (Nagarajaiah *et al*., 2010). This presented a very important step forward. Nonetheless, the 2011 Tohoku earthquake revealed that “damage free” cities are far from being a reality. This is for several reasons: For one, even if the technology matures, existing “non-damage free” buildings will probably still exist in the near to far future. In addition, structural systems are damage-free only up to the level of seismicity for which they were designed to remain undamaged, if such a design was feasible. Moreover, as mentioned earlier, the overall performance of a building is also strongly governed by the performance of other entities. In view of the above, minimizing the effect of the ground motion and its disruption to normal functionality is very important and, indeed, requires more research. Nonetheless, increasing the slope of the recovery phase (Stage II), or the “rapidity” as defined by Bruneau *et al*. (2003), will always play an important role in a quick recovery process.

In order to identify future research directions, the timeline and needs for earthquake mitigation and recovery is presented. Figure 2 shows these needs on the timeline of earthquake mitigation and recovery. They are:

(1) Event (shaking and tsunami) magnitude and effect prediction: Reliable predictions of the loading magnitude are of great importance. These predictions determine the level of resistance that civil structures are designed for and the level of preparedness of emergency entities at the national level. Their importance is manifested by the 2011 Tohoku earthquake and the subsequent tsunami where a huge loss was a result of effects that were larger than predicted.

(2) Design and retrofitting of structures and infrastructures: Appropriate seismic resistance of infrastructure and individual civil structures would minimize their damage. This is relevant in the design of new structures and in the retrofitting of existing ones. This, in turn, would decrease the initial disruption to

normal functionality. As a consequence, a quick recovery would be made much easier and require less efforts and resources.

(3) Real time prediction: The term real time prediction refers here to real time sensing of the seismic event parameters and the prediction of its effects. A real time prediction of the event a very short time before it takes place is crucial for taking immediate actions to minimize its effects (see Need 4 below). This is defined herein as real time prevention of damage. Furthermore, a real time prediction of the event's effects could make crisis management much more efficient. Thus, this real time prediction supplies crucial data for Needs 4 and 5 below and is of critical importance.

(4) Real time prevention: With real time prediction at hand, real time prevention could be made possible. Real time prevention refers here to early warning systems as well as shut down systems for functions where damage may endanger a large population (e.g., nuclear power plants, plants working with hazardous materials, etc.). As the research needed for real time prevention in not related to structural engineering, it will not be further discussed here.

(5) Crisis management: The emergency resources available to mitigate extreme events are limited. Furthermore, efficient performance of one emergency entity relies on the actions of another. Thus, a well-coordinated collaborative effort of the different emergency entities is often required. In such cases, efficient crisis management is of great importance in enabling a quick recovery.

(6) Longer term recovery: In some cases, the effect of the event is to the extent that a large population is moved from its residential area. Examples are washed away villages or nuclear affected areas. In these cases, long-term strategies for rehabilitation of a community as a whole are required. As this requires research mostly on the political/societal side, it is not further discussed here

3 Research needs

The timeline of earthquake mitigation and recovery presented above manifests the need for research on related topics. Items 1 and 2 are very important in reducing the number of casualties as well as in reducing stage I events, that strongly affect the recovery time in Stage II (see Fig. 1). Items 3 and 4 are very important in both reducing the impact of Stage I as well as in having a steep inclination, or rapidity, in Stage II. Items 5 and 6 enable a steep inclination in Stage II. In some of the topics to be discussed, structural earthquake engineers may be able to contribute in a significant way. These topics are discussed in detail in this section. Note that these topics are based on the lessons learned from the 2011 Tohoku earthquake.

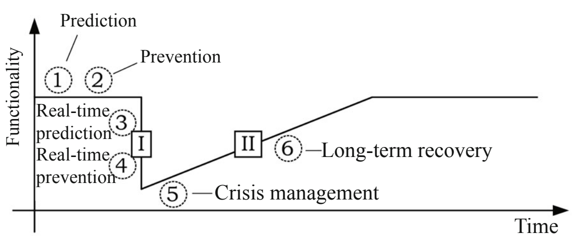

Fig. 2 Earthquake mitigation needs on the timeline of earthquake mitigation and recovery

3.1 Research Need 1: event magnitude and effect prediction

Prediction of ground motions and consequential tsunamis is a crucial step in preparedness and response. In Japan as an example, as noted above, the magnitude of rupture experienced in the 2011 Tohoku earthquake was not well predicted by existing models. The importance of updating these prediction models is manifested as similar models have been used to predict potential events due to the Nankai Trough. This trough produces a strong earthquake every 100-150 years, and the last one was experienced in the middle of the last century. Hence, it is believed that the next event will occur in the not so distant future. As in the 2011 Tohoku earthquake, the magnitude of the next event might be larger than expected. In order to better prepare for such events, prediction efforts are constantly made, and new models for prediction are continuously formulated.

3.2 Research Need 2: analysis, design and retrofitting of structures and infrastructure

The importance of analysis, design and retrofitting of civil structures and infrastructure is well known and has been discussed for some years. Here the focus is on the following topics: analysis of buildings to collapse; anti-liquefaction design; tsunami mitigation; damage free technologies for buildings and infrastructure; and seismic retrofitting. While some of these topics are new, others have been well-known for many years. These existing topics are re-emphasized in view of the lessons learned from the 2011 Tohoku earthquake.

3.2.1 Collapse prediction

In many modern large cities around the world, high-rise buildings are an inseparable part of the landscape. The catastrophe associated with the collapse of a high-rise building is huge. The performance of high-rise buildings under the 2011 Tohoku earthquake, in terms of structural damage, was reasonable. This is albeit the fact that, due to the magnitude of the event, the frequency content of the ground motion spanned over a wide range that includes those of high-rise buildings (Nakashima *et al.*, 2012). Nonetheless, high-rise buildings are expected to experience much stronger seismic excitations in the future. Hence, their ability to sustain the shaking without collapse is a major concern.

Stronger shaking of high-rise buildings, in Japan as an example, is promoted by several factors. For one, somewhat stronger earthquakes are expected to be produced by the Nankai Trough if its three regions rupture simultaneously. These may also have epicenters closer to areas with a much larger population of high rise buildings than that exposed to the 2011 Tohoku earthquake. In addition, the site effects in the regions populated with high-rise buildings is expected to be more detrimental in this case. This is because its natural period is much closer to that of high-rise buildings.

In general, structures are seismically designed for a certain level of performance under expected levels of ground motions. Their behavior under stronger ground motions is generally not known. The distance from the level of ground motion in design to the level of ground motion that leads to a complete collapse of a building is the collapse margin (see e.g. FEMA, 2009; Zareian *et al*., 2010). As ground motions larger than expected do occur, it is important to be able to quantify the collapse margin. In analysis up to collapse, physical phenomena that had a minor effect under moderate vibrations take an important role. Examples are fracture and geometric nonlinearity both at the local and global levels. Thus, much more complex behavior is expected. This presents increasing difficulty in the prediction of collapse. In that context, emphasis should be given to the collapse prediction of high-rise buildings. This is due to the fact that there is much less experience, research and knowledge related to the factors promoting their collapse compared to that of low rise buildings. Furthermore, relatively, there is lack of research on the characteristic parameters of earthquakes in the long period range. Thus, it is more likely that high-rise buildings would be taken beyond their design limits. In view of the above, reliable analysis and simulation methods for high-rise buildings up to collapse should be sought and verified through experiments.

3.2.2 Anti-liquefaction design

Collapse due to vibrations is not the only cause for failure of buildings. The liquefaction experienced in many regions due to the 2011 Tohoku earthquake also caused massive damage. Liquefaction occurred especially in reclaimed lands, even though far from the epicenter (e.g. Tokyo, Chiba). This is probably due to the differences in the behavior of reclaimed soil compared to natural soil as well as the generally low height of reclaimed land above sea level. This is also attributed to excitations comprised of small to medium amplitudes but with many cycles. Thus, new theory and analysis tools, as well as liquefaction criteria, are required, and anti-liquefaction design methodologies and measures should be developed.

3.2.3 Tsunami mitigation

Another major source of damage experienced due to the 2011 Tohoku earthquake is related to tsunami. The 2011 tsunami washed away many reinforced concrete buildings. In principal, the physical phenomena causing structures to be washed away by tsunami can be identified, and analysis tools as well as anti-tsunami design methodologies can be established. Nonetheless, it is the authors' feeling that this would require much research on the one hand, and is of limited importance on the other. This is mainly due to the height of most buildings compared to possible tsunami height. The tsunami height due to the 2011 Tohoku earthquake often reached more than 10 m, and occasionally even up to 20 m. Thus, buildings of up to five stories would all be covered by such a tsunami. These could, hence, not serve as a shelter and would have to be evacuated before the inundation. It is therefore considered more sensible to invest in escape routes to higher ground.

3.2.4 Structural and nonstructural damage-free designs and technologies

Prevention of failure of structural systems is the first task of earthquake engineering, as it is directly related to prevention of loss of human lives. As is evident from the response of the population to the results of the 2011 Tohoku earthquake, prevention of loss of human lives is indeed important, but is not sufficient. Functionality of buildings and facilities is a very important aim as well. The development of damage free designs and technologies (up to a point), related to both structural and nonstructural damage, is indeed underway, as noted in Section 2. Nonetheless, more research is needed in this direction.

At this point it should be emphasized again that good performance of the individual structure is not sufficient. The performance of a structure strongly depends on the performance of other entities within the same society (e.g. utilities, lifelines). Thus, in this context, efforts to develop damage free lifelines and utilities should also continue.

3.2.5 Seismic retrofitting

Lessons learned from the 2011 Tohoku earthquake indicate that, in terms of structural damage, older buildings present the weak link. Such buildings will still be a part of the landscape throughout the world in the near to far future. Hence, efforts should be made to retrofit them. This is also motivated by the updated predictions of seismic hazard as well as the performance requirements from buildings that keep increasing. In addition, the current understanding of seismic behavior requires more stringent demands (detailing, ductility capacity) than those required in the past, even for the same level of performance. Thus, technologies and design approaches for seismic retrofitting are required. This has also been the subject of research for many years, and here too, more research is needed.

3.3 Research Need 3: real time prediction

3.3.1 Definition and purpose

The term real time prediction refers here to real time sensing of the seismic event parameters as well as real time sensing and prediction of its effects. The final goal is twofold: (1) to enable efficient real time prevention of damage by means of early warning and automatic shut-down systems, as noted in Section 2;

and (2) to provide real time damage information at the local (individual building) and global (city) levels. This is essential for crisis management as good decision-making in the immediate response to the disaster heavily depends on the availability of data. Thus, continuous flow of information should be supplied to the disaster prevention authorities including the cabinet office, local governments, companies, organizations, etc. This will also assist individuals and groups to obtain real time information and act accordingly to achieve disaster resilience strengthening. Here the focus is on real time prediction of tsunami inundation; condition assessment of buildings using health monitoring approaches; and real time sensing and analysis at the city block level.

3.3.2 Tsunami

The 2011 Tohoku earthquake and subsequent tsunami claimed over 18,000 lives. Out of these, over 95% are attributed to the tsunami, mostly due to drowning. Hence, it is of great importance to develop real time prevention capabilities in the form of early warning systems and real time evacuation routes information systems to prevent loss of life in the future. For this purpose, real time prediction of tsunami and the expected regions to be affected is required. Here, “real time prediction” means within a few minutes after the seismic event.

In the context of tsunami prediction, the task could be divided to two sub tasks. One is related to an advanced measuring while the other is related to a reliable analysis for prediction of the tsunami inundation. Regarding the first sub-task, innovative and trustworthy technology that directly measures generated tsunami height should be developed. This could be based on seabed pressure gauges, GPS-based ocean wave meters and alike. Regarding the second sub task, a reliable tsunami propagation simulation technology that relies on advanced theory should be developed. Here, the influences of coastal landform that often has a complex geographical shape should be considered. For this purpose, accurate geographical data is required.

Research related to these two directions would allow a real time prediction of the locations to be flooded. Thus, it is believed that with such real time prediction capabilities, appropriate guidance could be given to the population regarding safe locations and routes for evacuation. This could be a key feature in saving lives from future tsunamis. In addition, such information could be very valuable for decision makers.

3.3.3 Monitoring

When severely shaken, structures may exhibit structural damage that can jeopardize their ability to resist aftershocks without collapse. Nonetheless, to assess their structural vitality, a thorough inspection by engineers is required. Even with such an inspection, a guarantee cannot be given as eye detection of structural damage, which may often hide behind nonstructural components, is not an easy task. Thus, the population often faces questions regarding whether or not one can stay in a building or if it should be evacuated. More importantly, answers to such question are required in a timely manner (within a few minutes). Otherwise, the population will evacuate buildings that may be safe. In some locations, this may not pose any issue. However, in the heart of large cities, which are often populated with many high-rise buildings containing thousands of people, this may lead to a disaster. From another point of view, in high-rise buildings located in downtown Tokyo, for example, the headquarter offices of about 20% of the companies whose stock are open to the Tokyo stock market are located. Their sales amass to about 30% of Japan’s total economy. The continuation of these businesses is financially crucial. Evacuation of such buildings, if they are safe, will cause huge unnecessary financial losses. Apart from the population local use of the acquired data from the monitoring systems, data regarding the condition of these buildings is crucial for decision-making.

For this purpose, more advanced sensing and monitoring technologies as well as theory for an immediate condition assessment and structural health evaluation are essential. To allow monitoring of a building that enables meaningful and detailed condition assessment, many sensors are required. Hence, on the technological side, the challenge is to develop low cost, handy and durable advanced sensors. On the condition assessment side, advanced theory should be developed. This research topic is not new. However, structural health monitoring in this context requires much further research.

3.3.4 Sensing and analysis at the city level

As it is unlikely that all buildings would be monitored, for the sake of decision-making, alternative means for condition assessment at the city block level should be developed. One approach to attain such alternative means is by developing capabilities for an approximate, quick but meaningful analysis at the city block level. Such analysis capabilities should be based on available data. In additions, efforts should be made to generate available data that would enable such analysis capabilities.

To obtain this data, a dense mesh of sensors to measure the ground motion history, on the order of hundreds of thousands of them, is required. The density of this mesh depends on the density of the building block at a given location. In populated areas in Japan, for example, a grid of 250 m × 250 m would probably be required. That amounts to 16 sensors in one square kilometer. For that to become a reality, inexpensive sensors, probably with no individual data acquisition for each sensor, are to be developed. These should probably be associated with a cloud technology. Such a system should continuously keep data flowing to a central server.

With such data becoming available, structural analysis theory and application to allow simulation at the level of a city block, should be developed. As indicated, these analysis capabilities should be based on the available and limited data, be as real time as possible (that is, very short computational and communication time), and produce results as reliable and meaningful as possible.

To enable such an analysis, the data of the ground motions by itself is not sufficient. Data of the building stock is also essential. Here, two obstacles are apparent. The first relates to data sharing. That is, even though some data is documented, it is not necessarily available due to privacy issues. Furthermore, even if the issue of privacy is resolved and the data is indeed available, another obstacle arises. Collection and digitization of the data to a level that is detailed enough for use in structural models is impractical in a reasonable time before the next big earthquake. If not done automatically, this may take several decades. Hence, automatic collection and interpretation of data to best represent the structural system and enable attaining models that would allow meaningful analyses to be conducted is needed. This can rely on existing documentation as well as on new theories to automatically interpret the structural system based on digital photos, satellite images and alike.

3.4 Research Need 5: crisis management

Right after the 2011 Tohoku earthquake, some data regarding the tsunami, the condition of the nuclear power plant, transportation, utilities, etc., was available. However, it was not properly and accurately conveyed to each crisis management entity (hospitals, firefighters, transportation, etc.), each lifeline company (electricity, water supply and alike), companies that supply essential groceries and merchandise, and finally every person. Thus, resources were not efficiently used and corresponding actions were not efficiently taken. In turn, this led to loss of human lives. Furthermore, the inclination of the recovery stage (Stage II in Fig. 1) was not as steep as it could be. Thus, the period of recovery was much longer than it should have been.

In modern societies, all crisis management entities and all lifeline companies, as well as their actions for quick recovery, are mutually dependent. Failing to work in good coordination appreciably reduces the effectiveness and recovery abilities of these societies. Thus, global crisis management is of great importance. The dependence of all entities on each other also makes crisis management much more complex. Hence, data, information and tools that would assist crisis management are very important. These can assist not only in managing resources, but also in the restoration of lifelines, utilities and medical services.

To enable efficient crisis management and control capabilities, processed and interpreted data should constantly flow to the crisis management entities and to lifeline companies. As will be discussed, several obstacles to enable this dataflow should first be overcome. These are: data sharing privacy issues; technical issues associated with the amount of data and reliability of the data sharing platform in case of an event; automatic interpretation of data; decision-making support algorithms; collaborative effort of all entities; and automatic information sharing with the public.

3.4.1 Data sharing privacy issues

Currently, the majority of data required for crisis management is owned by private citizens and companies. As already indicated, privacy issues restrict the sharing of data related to the structural systems of buildings. The same privacy issues restrict the sharing of acceleration history records of accelerometers mounted on privately owned high-rise buildings, lifeline state, merchandise supplies and more. While such data is essential for efficient crisis management, privacy issues prevent the sharing of this data between crisis management entities and companies. Hence, such privacy issues should be removed and entities should be motivated to share their data in times of crisis. This has been said many times but has not been applied to the extent required. Hence, a mechanism for the different players consent to share information should be formed.

3.4.2 Technical issues associated with the amount of data and reliability

Privacy issues do not pose the only obstacle for data sharing. The amount of data to be shared, coming either from companies through a designated framework or from individuals through smart phone applications, is huge. Naturally, this poses a technical issue associated with handling and sharing such mega-data. To allow that, efficient technology that would enable a platform for data sharing should be developed. Such a platform should be reliable in case of an earthquake. Thus, it should be robust and not rely on a single communication technology. Furthermore, to prevent the transfer of large data files, the essential data should be automatically identified and culled. In addition, efficient data saving formats that will reduce the size of files to be transferred should be developed. Finally, the data should be securely handled.

3.4.3 Automatic interpretation of data

The raw data to be shared is very valuable and essential for crisis management. Nevertheless, such raw mega-data cannot be handled by people alone. Thus, automatic interpretation of the mega-data should be carried out to supply real time interpreted and useful damage and resources information for decision making entities. For this purpose, theories and methods should be developed to identify the important pieces of information, process it, complete the puzzle and present a clear map of the damage state, lifeline locations, supplies availability, population location, etc.

3.4.4 Decision-making support algorithms

A complete and clear map of damage state, resources and more would indeed present "the whole picture" to decision makers. This, by itself, is indeed an important and valuable tool. To further assist the decision makers in managing the crisis, development of decision-making support algorithms should also be sought. Each emergency entity or lifeline company (e.g., electric, communication, railway, infrastructure, and small companies) has its own policies, organizational structure and working methods. Thus, the developed algorithms should, at the first stage, be client oriented. Due to the strong dependency between the different entities, at a later stage, interaction between lifeline companies could be taken into account. Finally, it should be the goal to integrate all individual algorithms to enable a truly efficient crisis management capability.

3.4.5 New mechanisms to ensure collaborative effort

For the purpose of integrating all individual algorithms, and more importantly to allow a truly efficient crisis management, new mechanisms to ensure collaborative effort of these entities are required. As stated earlier, there is mutual dependence between the actions of different entities. For example, an operational hospital cannot serve patients if the access roads are blocked. In this case, firefighters are required to clear the roads. Thus, collaborative efforts are very important in enabling a smooth and quick recovery. This would also prevent duplication of resource usage. Currently, in case of a disaster, each emergency entity is focused on its own mission; new mechanisms to ensure and to manage collaborative efforts are needed.

3.4.6 Information sharing with the public

In case of a disaster, common media such as landline telephones, cell phones, Internet, etc. may be damaged or overloaded. Even so, as noted above, sharing information with the public is of great importance. Hence, similar as discussed in Section 3.4.2, the development of communication technologies for these cases is needed. Although different in nature, as with the data supplied to decision makers, the information shared with the public should be condensed but meaningful. In this case, the position of the individual who seeks information should be identified and the information should be location based.

4 Current research and development efforts in Japan

As a response to the lessons learned from the 2011 Tohoku earthquake, a few comprehensive research and development efforts have been undertaken in Japan. Below is a partial list of these efforts:

(1) Research Project for Compound Disaster Mitigation on the Great Earthquakes and Tsunamis around the Nankai Trough Region (PI: Japan Agency for Marine-Earth Science and Technology – JAMSTEC; eight years starting in 2013): Regional collaborative research is ongoing for earthquake and tsunami disaster mitigations, e.g., recovery planning, damage prediction and data sharing, and survey research on fault mechanism and tsunami simulations.

(2) Development of Ocean Bottom Earthquake and Tsunami Observation Networks around Japan Trench (PI: National Research Institute for Earth Science an Disaster Prevention – NIED; three years between 2012 and 2014): Deployment of an ocean bottom network composed of cabled seismographs and tsunami sensors is in progress for continuous monitoring of seismic motions and sea level changes near earthquake sources.

(3) Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters (PI: DPRI of Kyoto University; five years starting in 2012): Targeted are the collection and dissemination of experimental data on damage and collapse of high rise buildings, implementation of advanced health monitoring networks, and refinement of simulation and assessment of soil-foundation-structure interaction.

(4) Enhancement of Societal Resiliency against Natural Disasters (PI: Cabinet Office of Japan; five years starting in 2014): The main goals include monitoring and prediction of natural disasters, enhancement of anti-liquefaction measures, data sharing by the establishment of a resilience information network, and crisis management.

5 Summary and conclusions

This paper presents research needs identified based on lessons learned from the 2011 Tohoku earthquake. First, the timeline of earthquake mitigation and recovery, as seen by the authors, is presented. Based on this timeline, important known research needs, where much research is still needed, and important new research needs are identified.

The research needs include the following:

- Prediction of ground motion and tsunami parameters, where much efforts have been carried out but prediction models are to be constantly updated
- Seismic design and retrofitting of structures, where focus should be given to:
  - Continuous efforts for prediction of collapse of high-rise buildings due to the lack of knowledge and experience as to their collapse margin.
  - Anti-liquefaction design, where theory and analysis tools are needed, particularly for reclaimed land, while considering many cycles of vibration.
  - Anti-tsunami design, where early warning systems and real time prediction capabilities of inundated regions are required.
  - Continuous efforts for invention and development of structural and nonstructural damage-free designs and technologies for buildings and infrastructure.
  - Continuous efforts for invention and development of seismic retrofitting designs and technologies.
- Real time prediction:
  - Real time prediction of tsunami inundation locations and height that will allow identification of escape routes and safe locations.
  - Monitoring of high-rise buildings that will allow their continuous occupancy and operation in case they are safe.

○ Sensing and analysis at the city block level that will allow efficient decision-making.

- Crisis management, where the following issues are needed to be resolved:

○ Data sharing privacy issues, where some privacy issues should be removed and new mechanisms should be formed to motivate the various players to share data in case of a disaster.

○ Methodologies to overcome technical issues associated with the amount of data and reliability should be developed.

○ Automatic interpretation of data, where the raw data is automatically screened and interpreted to real time useful damage and resources information for decision making entities.

○ Development of decision-making support algorithms for disaster management to allow a truly efficient crisis management, where all entities efficiently collaborate.

○ To allow a truly efficient crisis management, new mechanisms to ensure collaborative efforts are needed.

○ Development of approaches for information sharing with the public, where important and processed location based data is supplied.

Furthermore, the currents research and development efforts in Japan following the 2011 Tohoku earthquake are presented. These efforts show that steps are already being taken to close the gap in knowledge and prepare for the next earthquake.

References

Architectural Institute of Japan (AIJ) (2011), *Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake.* (in Japanese)

Architectural Institute of Japan (AIJ) (2012), "Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake," *Geotechnical, Geological and Earthquake Engineering 23*, ISBN: 978−4−431−54096−0, Springer, 460p.

Bruneau M, Chang S, Eguchi R, Lee G, O'Rourke T, Reinhorn A, Shinozuka M, Tierney K, Wallace W and von Winterfelt D (2003), "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities," *Earthquake Spectra*, **19**(4): 733−752.

Bruneau M and AM Reinhorn (2007), "Exploring the Concept of Seismic Resilience forAcute Care Facilities," *Earthquake Spectra*, **23**(1): 41−62.

Building Center of Japan (BCJ) (1981), *Structural Provisions for Building Structures−1981 Edition*, Tokyo, Japan. (in Japanese)

Christopoulos C and Filiatrault A (2006), *Principles of Passive Supplemental Damping and Seismic Isolation*, IUSS Press.

Cimellaro G, Fumo C, Reinhorn AM and Bruneau M (2009), *Quantification of Disaster Resilience of Health Care Facilities*, Multidisciplinary Center for Earthquake Engineering Research, MCEER−09−0009.

Cimellaro GP, Reinhorn AM and Bruneau M (2010), "Framework for Analytical Quantification of Disaster Resilience," *Engineering Structures*, **32**(11): 3639−3649.

Cornell CA (1968), "Engineering Seismic Risk Analysis," *Bulletin of the Seismological Society of America*, **58**(5): 1583−1606.

Federal Emergency Management Agency (FEMA) (1997), *NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA−273*, Federal Emergency Management Agency, Washington, D.C.

Federal Emergency Management Agency (FEMA) (2009), *Quantification of Building Seismic Performance Factors, FEMA−P695*, Federal Emergency Management Agency, Washington, D.C.

Iemura H and Pradono MH (2002), "Passive and Semi-active Seismic Response Control of a Cable-stayed Bridge," *Journal of Structural Control*, **9**(3): 189−204.

Kelly JM and Naeim F (1999), *Design of Seismic Isolated Structures: From Theory to Practice*, Nueva York, John Wiley & Sons.

Mori J and Eisner R (2013), *Special issue: 2011 Tohoku-Oki Earthquake and Tsunami*, *Earthquake Spectra*, **29**(S1).

Mori N, Cox DT, Yasuda T and Mase H (2013), "Overview of the 2011 Tohoku Earthquake Tsunami Damage and Its Relation to Coastal Protection along the Sanriku Coast," *Earthquake Spectra*, **29**(S1): 127−143.

Nagarajaiah S, Reinhorn AM, Constantinou MC, Taylor D, Pasala DTR and Sarlis AAS (2010), "True Adaptive Negative Stiffness: A New Structural Modification Approach for Seismic Protection," *Proceedings of 5th World Conference on Structural Control and Monitoring*, July 12−14, 2010, Tokyo, Japan.

Nakashima M, Becker TC, Matsumiya T and Nagae T (2012), "A Lesson from the 2011 Tohoku Earthquake-The Necessity for Collaboration and Dialog among Natural Scientists, Engineers, Social Scientists, Government Agencies, and the General Gublic," Chapter 13, *Performance-based Seismic Engineering: Vision for an Earthquake Resilient Society*, Editor: M. Fischinger, Springer, 2014.

NILIM and BRI (2011), "Summary of the Field Survey and Research on 'The 2011 off the Pacificcoast of Tohoku Earthquake' (the Great East Japan Earthquake)," September 2011, http://www.kenken.go.jp/english/contents/topics/20110311/0311summaryreport.html.

Priestley MN (1996), "The PRESSS Program: Current Status and Proposed Plans for Phase III," *PCI journal*, **41**(2): 22−40.

Reitherman B *et al*, (1995), "Nonstructural Damage," *Earthquake Spectra*, **11**(S2): 453−514.

Renschler CS, Frazier A, Arendt L, Cimellaro GP, Reinhorn AM and Bruneau M (2010), *A Framework for Defining and Measuring Resilience at the Community Scale: The PEOPLES Resilience Framework*, MCEER−10−0006.

SEAOC (1995), *Vision 2000*, *Performance Based Seismic Engineering of Buildings*, Sacramento (CA): Structural Engineers Association of California.

Skinner RI, Robinson WH and McVerry GH (1993), *An Introduction to Seismic Isolation*, Wiley, Chichester, England.

Soong TT and Dargush GF (1997), *Passive Energy Dissipation Systems in Structural Engineering*, ISBN: 978−0−471−96821−4,Wiley, 368 Pages.

Villaverde R (1997a), "Method to Improve Seismic Provisions for Nonstructural Components in Buildings," *Journal of Structural Engineering*, ASCE, **123**(4): 432−439.

Villaverde R (1997b), "Seismic Design of Secondary Structures: State of the Art," *Journal of Structural Engineering*, ASCE, **123**(8): 1011−1019.

Zareian F, Lignos DG and Krawinkler H (2010), "Evaluation of Seismic Collapse Performance of Steel Special Moment Resisting Frames Using FEMA P695 (ATC−63) methodology," *Proceedings of Structures Congress ASCE*, Orlando, FL.