

IMPLICATIONS OF THE GREAT EAST JAPAN EARTHQUAKE FOR THE PACIFIC NORTHWEST REGION OF THE UNITED STATES

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ABSTRACT: Engineers from the Structural Engineers Association of Washington studied the earthquake and tsunami damage caused by the Great East Japan Earthquake. This team's objective was to understand the effects of this event, because a similar earthquake and tsunami could occur along the Cascadia Subduction Zone, near the Pacific Northwest Coast of the United States. This paper is a brief summary of the team's observations and the lessons learned that may be applied to earthquake engineering and emergency planning practices in the Pacific Northwest region.

Key Words: Great East Japan Earthquake, SEAW, reconnaissance, observation, lessons learned, Pacific Northwest, Cascadia Subduction Zone, tsunami damage

INTRODUCTION

On Friday, March 11, 2011 at 2:46 PM (local time), the Northeast coast of Japan was struck by a magnitude 9.0 (M 9.0) subduction zone earthquake as the boundary between the Pacific and the North American plates ruptured along an offshore section. The rupture extended more than 300 km (200 miles) along the Japan coast, causing strong ground shaking that lasted for several minutes, and a

devastating tsunami. A similar event along the Cascadia Subduction Zone, just off the Pacific Northwest Coast of the United States, would extend from Vancouver Island (Canada) to Northern California.

Recognizing the impacts that an earthquake of similar magnitude would have on the Pacific Northwest region of the United States, the Structural Engineers Association of Washington (SEAW) formed a reconnaissance team of engineers to observe and evaluate earthquake and tsunami damage in the affected areas. The team traveled to the Tokyo and Sendai areas, and along the Tohoku coast to observe the impacted areas. The team also met with Japanese earthquake research organizations, design and construction professionals, and public officials to learn more about the extent of the damage and seismic design practices in Japan. Figure 1 shows the sites that the team visited in Miyagi Prefecture.

This paper provides a brief summary of the team’s observations and the lessons learned that may be applied to earthquake engineering and emergency planning practices in the Pacific Northwest region of the United States. Observations and findings related to a number of topics are presented. These include seismology, geotechnical effects, building performance, high-rise buildings, earthquake protective systems, tsunami damage in coastal towns, roads and bridge performance, industrial facilities and lifelines, and preparation, response, and recovery.

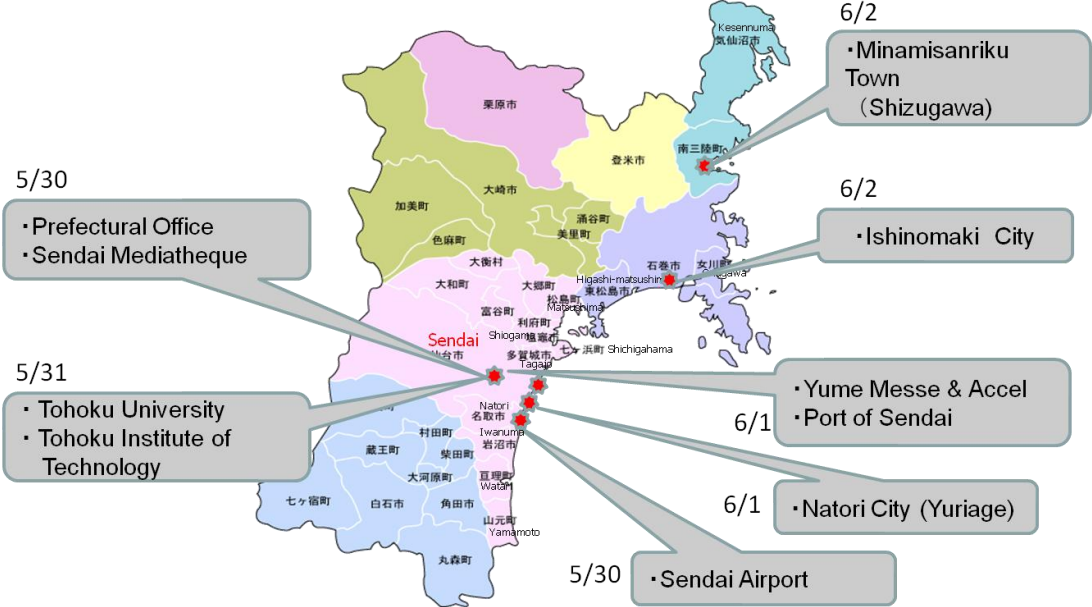


Fig. 1 Sites visited by the SEAW reconnaissance team in Miyagi Prefecture and dates visited

SEISMOLOGY

There are striking similarities between the geological setting of the Great East Japan Earthquake and the geological setting along the Pacific Northwest Coast of the United States. Figure 2 shows the approximate fault rupture area related to the M 9.0 main shock of March 11, 2011, and the estimated fault rupture area that could be associated with a M 9.0 subduction zone event in the Cascadia Subduction Zone off the coast of Washington, Oregon, and northern California in the United States (USGS 2011).

Geological studies have found that as many as seven subduction zone earthquakes have occurred during the last 3,500 years along the Pacific Northwest coast. The most recent of these was 312 years ago, on January 26, 1700 (Atwater et al. 2005). The average return time for these events appears to be in the range of 300 to 600 years. Thus, because there is at present a very real possibility of a subduction zone earthquake occurring in the Cascadia Subduction Zone, and because such an event would have

consequences similar to the Great East Japan Earthquake, the SEAW team felt it was imperative to visit the Tohoku area and learn as much as possible about damage caused by the earthquake and tsunami.

Hundreds of accelerograms were recorded during the main shock and subsequent aftershocks of the Great East Japan Earthquake, providing an unprecedented body of ground motion data from a subduction zone earthquake. This data will be extremely useful in predicting the effects of future subduction zone events, for the study of ground motion characteristics such as topographic effects, and for use in the analysis of future building and bridge designs.

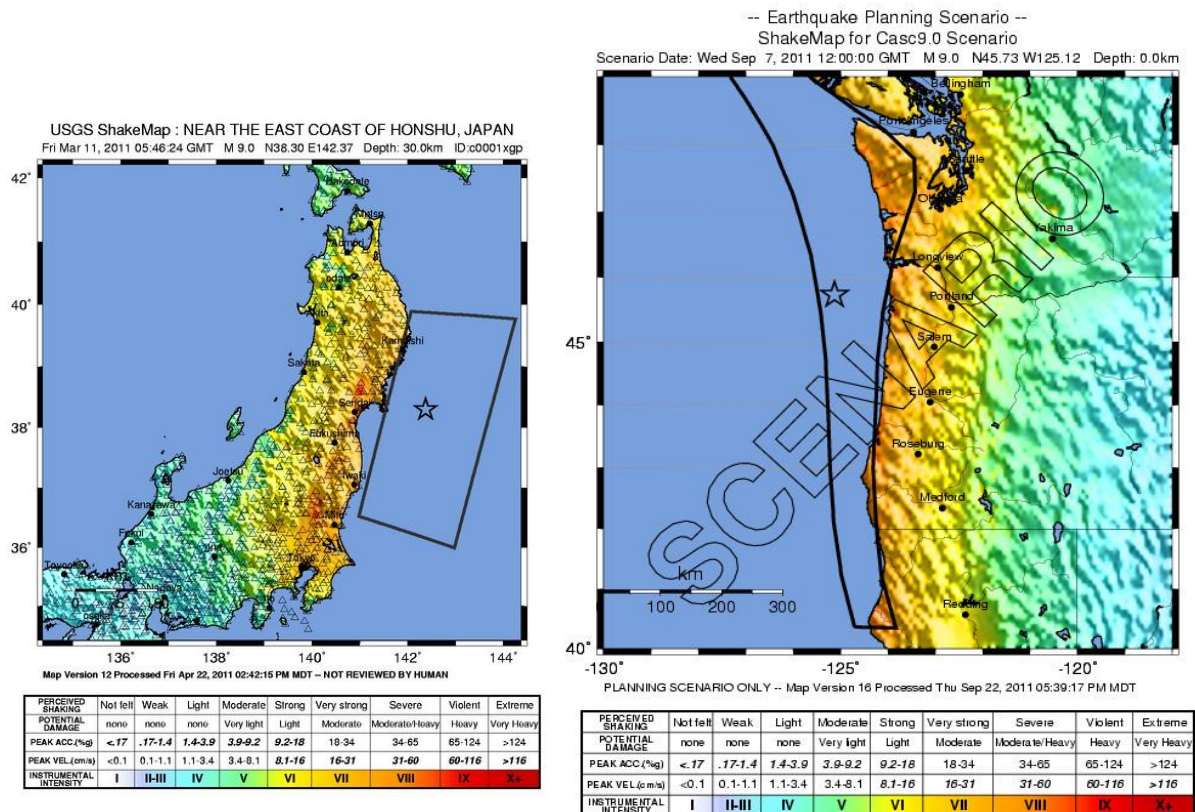


Fig. 2 Approximate fault rupture area of M 9.0 main shock of March 11, 2011 (left), and approximate fault rupture area of hypothetical M 9.0 Cascadia Subduction Zone event (right). (Graphics courtesy of United States Geological Survey)

GEOTECHNICAL EFFECTS

The team observed that earthquake damage related to geotechnical effects generally occurred in known geologic hazard areas. For example, landslides and rockfalls generally occurred in areas of past instability. Liquefaction occurred in areas with loose to medium-dense, saturated sand and silt, especially in areas of reclaimed land (e.g. at Urayasu City in the metropolitan Tokyo area).

Liquefaction damage was extensive, even at sites over 150 km from the fault rupture. Examples of observed liquefaction damage include damage to structures caused by ground movement and lateral spreading toward bodies of water. Liquefaction caused ground and utility line settlement that resulted in breaks where utilities entered pile-supported structures. Some inadequately designed pile foundations were damaged by liquefaction. Sand boils appeared at the ground surface in some liquefaction zones. These sand boils sometimes limited earthquake recovery. Several cases were observed where liquefaction caused pipelines, manholes, and vaults to float out of the ground.

The team observed that ground improvement measures are effective in mitigating liquefaction-induced damage. Existing engineering methods appear to provide reasonable estimates of

the likelihood and effects of liquefaction. Newer structures that were designed for known geologic hazards performed well under the long-duration ground shaking imposed by this earthquake.



Fig. 3 Performance differences between adjacent buildings supported on piles versus shallow foundations in Urayasu City (Lindquist)

BUILDING PERFORMANCE

Japan’s modern design codes consider seismic hazard levels that are similar to current U.S. codes. One exception is that in some cases Japan’s codes require higher design forces for very flexible, long-period structures (e.g., some high-rise buildings). In addition to life-safety seismic performance, Japan’s codes require considerations of building functionality following a moderate earthquake.

Buildings designed under recent Japanese design codes (post-1980) performed well during this earthquake, with limited structural damage. However, costly non-structural damage was common, largely due to situations where there was a lack of seismic restraints for building contents and building systems. As a result, it is anticipated that the Japan national standard for non-structural elements will be revised based on data obtained from this earthquake.

The team observed no structural failures of modern buildings (unless other factors were involved, such as poor soil conditions), but older/non-ductile buildings experienced damage. In many cases, structural configuration irregularities (mass eccentricity, stiffness discontinuity, strength discontinuity, etc.) in combination with soil or topographic conditions were major contributing factors to damage.

Seismically retrofitted buildings are common in Japan. Retrofitted buildings performed well, demonstrating that seismic retrofitting is a very effective way to preserve older buildings in a high seismic zone. Buildings in the Pacific Northwest are expected to perform similarly to buildings in Japan: newer buildings should do well but older buildings (without seismic retrofits) are likely to be damaged. Contents and equipment (non-structural elements) are likely to be heavily damaged in many buildings. Design beyond life safety (i.e., occupiable design) is needed for true seismic resilience of communities in the Pacific Northwest.



Fig. 4 Retrofitted buildings in central Sendai (left) and Tohoku University (right) (Siu)

HIGH-RISE BUILDINGS

No reports of structural damage to high-rise buildings in Miyagi Prefecture (Sendai) and Tokyo were made, but there were many reports of non-structural damage (building contents, interior finishes, equipment) and loss of building systems, including water, sewer, gas and electricity.

The loss of building mechanical and electrical systems in residential structures over eight stories high led to “high-rise refugees”. Without power for elevators, residents could not reach their apartments and condominiums. Pumps providing water to upper stories were not operational, and without gas, residents could not heat their units or cook. The displaced population from high-rise buildings had not been anticipated in some earthquake planning scenarios, illustrating that life-safety seismic performance is not enough. High-rise buildings, in particular, must be habitable after a major earthquake.

Buildings in Japan are commonly outfitted with seismic sensors and shutoffs on gas and water systems. Backup generators provided emergency power to high-rise buildings immediately after the earthquake, but after the first 24 hours, additional fuel supplies were difficult or impossible to obtain.

BUILDING PROTECTIVE SYSTEMS

Since the 1990s, Japan has enthusiastically embraced special seismic protection systems for buildings. These include base isolation systems, where a building is placed on flexible or sliding supports, and damping systems, where damping devices are installed within the structural frame to absorb earthquake energy and reduce earthquake damage.

According to statistics published by the Japan Society of Seismic Isolation (JSSI 2012), as of 2009 Japan had over 2,600 commercial and multi-family residential buildings with seismic isolation systems, whereas Washington State has only eight such buildings. Japan has over 3,800 single-family homes with seismic isolation systems. In Washington State there is only one base-isolated single family home, which is currently under construction. Japan has over 1,000 buildings with earthquake damping systems. Washington State has only ten buildings with damping systems.

The Tohoku earthquake was a “living laboratory” for studying the performance of buildings with base isolation systems and damping systems. These systems performed as expected: in all cases studied by the team, the base isolation and damping systems provided effective control of damage to both

structural systems and non-structural elements. The Great East Japan Earthquake demonstrated that these systems worked well, and they should be considered more often for important structures and facilities in the Pacific Northwest.

TSUNAMI DAMAGE IN COASTAL TOWNS

The team visited several coastal towns along the Miyagi coast that experienced strong ground shaking followed by several tsunami inundation events (Figure 1). The region includes relatively flat coastline as well as hilly areas (north of Sendai). Table 1 summarizes tsunami impacts on the towns of Ishinomaki and Minamisanriku.

Table 1 Statistics for two coastal towns inundated by tsunamis (as of May 14, 2011, *Japan Times*)

Town	Ishinomaki (50% of town flooded)	Minamisanriku Town
Population	Approx. 160,000	Approx. 17,500
Perished	2,964 (2%)	514 (3%)
Missing	2,770 (2%)	664(4%)
Evacuees	8,780 (5%)	4,870 (28%)

The team met with local officials to discuss the tsunami damage and disaster response measures. In many coastal towns the tsunami wave heights far exceeded the maximum planning scenario. Nonetheless, state-of-the-art early warning systems and aggressive mitigation actions prevented an even larger catastrophe.

The region experienced more than two minutes of strong ground shaking followed by multiple aftershocks and tsunami inundations along the coast. Depending on the location, maximum wave heights ranged from 4.5 to 15 meters (15 to 50 feet) and overtopped coastal seawalls, as well as some multi-story structures that had been designated as vertical evacuation shelters. A seismic retrofit program instituted after the 1978 Miyagi-ken Oki earthquake proved effective. Retrofitted structures such as schools and hospitals survived the ground shaking and, in areas also inundated by tsunamis, provided reliable vertical evacuation shelters.



Fig. 5 Retrofitted school building (left) in Arahama Ward (Sendai) provided vertical shelter to the devastated community, where virtually no wooden structures remained (right) (Pierepiekarz)

Inundated wood-framed structures were mostly destroyed. Extensive debris impact damage to surviving wood-framed structures was evident. In inundation areas, erosion of building foundations and in-ground utilities was also very evident. Fire events followed tsunami inundation at a number of locations. Some inundated hybrid automobiles were reported to have shorted-circuited battery systems

which were reported to have started fires.

The coastlines of the Pacific Northwest (United States) and British Columbia (Canada) exhibit features that are similar to the east coast of Japan. A Cascadia Subduction Zone earthquake could generate strong ground shaking, tsunamis, and coastal elevation changes like those experienced in the Great East Japan Earthquake. The team made the following observations regarding preparation for a subduction zone event on the Pacific Northwest coast.

Extensive planning and mitigation activities are required in anticipation of a large-magnitude subduction zone event. Some planning has been accomplished for the Washington State coast, but progress on implementation of these plans is needed (<http://www.facebook.com/ProjectSafeHaven>). Early warning systems (tsunami and ground shaking) save lives and are needed along the Pacific Northwest coastline. Reliable vertical evacuation shelters are required in potential tsunami inundation zones. These structures must be sufficiently tall, allow access for the elderly and disabled population, be capable of surviving long-duration strong ground shaking, and resistant to multiple debris impacts. Coastal subsidence will affect local utilities and drainage patterns. A major earthquake and tsunami will require an extensive, multi-year cleanup and debris removal program. Continued study and application of best practices from Japan will improve the resilience of the Pacific Northwest coast in the event of a major Cascadia Subduction Zone earthquake.

ROAD AND BRIDGE PERFORMANCE

The following observations were made related to road and bridge performance. Ground-shaking damage to bridges was limited, due to adoption of modern seismic design codes and an aggressive seismic retrofit program implemented after the 1995 Kobe earthquake. Tsunami damage to bridges was primarily due to crossings with deep-profile girders, spans lacking vertical hold-down anchorage at supports, and scour at approaches. Many shallow-depth, short-span bridges survived many meters of tsunami inundation with repairable damage to their railings.



Fig. 6 Functional low-profile vehicle bridge in Ishinomaki City. Note damage from tsunami to leading edge of bridge walkway and guardrail on the left side of the photo (Swanson)

Roadways were damaged by the earthquake in thousands of locations due to embankment settlement or failure, bridge approach settlements, and lateral spreading. The extent of roadway damage impeded the disaster response and evacuations. After three months, most repairs were made with reduced speed limits necessary at many locations. The tsunami debris blocked most roadways in the inundation zones. This further impeded the disaster response. Roadway embankments overtopped

by the tsunami were typically severely damaged. Many roadway embankments that were not overtopped acted as barriers to the tsunami.

INDUSTRIAL FACILITIES AND LIFELINES

Industrial Facilities

The team observed earthquake impacts on several industrial facilities as well as critical utilities and lifelines. The observations included here are examples, rather than a comprehensive assessment of industry and utility damage. Significant regional industries in the affected Miyagi-ken area include agriculture, beverage and food processing, forest products, high-technology, petrochemical, ports, fishing, manufacturing, assembly, and steel mills. Earthquake impacts on these industries included ground shaking damage to structures and equipment (facility contents), as well as tsunami inundation (flooding), sometimes followed by fires.

Many industrial facility structures provided life-safety earthquake performance as intended by building codes for new construction. The extensive impacts and losses to the region and nation, however, indicate that performance beyond life-safety, such as “operational” or “functional”, may be required to achieve a resilient (i.e., quickly recoverable) status following a major event.

As shown by this event, in subduction-type earthquakes, facilities and lifelines located over 400 km from the epicenter (e.g. in the Tokyo metropolitan area) can be impacted. For industrial facilities, achieving acceptable seismic performance depends on the following factors: the facility location (elevation, soil conditions); critical services (bracing of services, impact of loss of services); tanks and piping (anchorage, debris impact); power supply (backup generators, long-term fuel supply); electrical equipment (equipment elevation, redundancy); fire-following-earthquake hazards (on- and off-site ignition sources); damage to suppliers (supply-chain dependency); customer impacts (effects on post-event sales); extent of debris (debris impact, and debris cleanup); available post-event resources (pre-arranged); and redundancy of operations.



Fig. 7 Underground utility impacts due to soil liquefaction in Chiba (Tokyo metropolitan area) (left), and fire-following earthquake impacts at Sendai Airport cargo area (right) (Pierepiekarz)

Lifelines

Lifelines include the external critical utilities and systems that a facility needs in order to remain functional. Examples of critical lifelines include water supply, sewer and wastewater treatment, power supply and distribution, communications, and transportation (highway, rail, airport, natural gas & fuel).

Although the team’s mission did not include a comprehensive treatment of lifeline systems, the

following observations and lessons can be applied to other regions prone to similar events, such as the Pacific Northwest.

Regarding water and sewer systems, it was observed that these systems were often disrupted by liquefaction damage to underground pipelines. In addition, coastal ground subsidence sometimes altered drainage patterns. Coastal water and sewer treatment facilities sometimes required extensive debris cleanup and repair of debris impact damage.

Some electrical supply systems at low elevations or in the lowest floors of buildings were damaged by tsunami inundation. Therefore, substations and electrical equipment should be located at the highest possible elevations. Some power poles in tsunami inundation areas were destroyed by scour and debris impact. Prolonged power shortages impeded repair and recovery efforts for industrial facilities.

With respect to communications systems, it was observed that some mobile telephone networks may not be reliable for up to a week after the event, due to network congestion, short-term availability of back-up power, and the long-term supplies of fuel for backup generators. Voice Over Internet Protocol (VOIP) and satellite systems were viable alternatives when mobile telephone network facilities were overloaded or not operational.

PREPARATION, RESPONSE, AND RECOVERY

These observations are based on discussions with officials from particular jurisdictions (prefectures, towns, or cities) in Japan and may not reflect issues in the entire affected area.

Preparation

Japan invested in physical barriers to protect coastal communities from tsunamis. Many of these barriers (e.g., seawalls, levees, and “tsunami forests”) proved to be ineffective because of the extreme heights of the tsunami waves generated by this earthquake.

Japan employs early-warning systems for ground shaking and tsunamis. These systems work to prevent injuries and save lives. The ground shaking warning system is readily available to everyone via mobile phones.

Japan regularly conducts drills for earthquakes and tsunamis. A town official in Minamisanriku Town reported a high degree of participation in their annual tsunami drills. These drills saved lives in this event, since “everyone in Japan knows where to go” in the event of a tsunami.

Schools and hospitals are used for vertical evacuation and shelter, and their location and height must be carefully considered. Minamisanriku Town relocated their schools to higher ground after a 1960 tsunami, and those schools were safe in the Great East Japan Earthquake. However, many patients in the town hospital were not evacuated to a high enough floor to be safe, because the hospital’s plan did not anticipate such large waves.

The Pacific Northwest has a number of coastal communities without accessible vertical evacuation facilities. These communities are vulnerable to widespread casualties from a Cascadia Subduction Zone earthquake and tsunami. Although some planning has been done in the Pacific Northwest for tsunami preparation and a few communities have begun implementation of those plans, much work needs to be done.

Response

Self-evacuations and rescue evacuations made it difficult for local authorities to get accurate counts of dead and missing people.

Earthquake-damaged roads and tsunami inundation slowed response. One group in Ishinomaki City, stranded on the upper floors and roof of their evacuation center, waited two to three days for food, medical supplies, and rescue evacuation. With the loss of their hospital, Minamisanriku Town had to wait over two weeks for a temporary field hospital to be set up. In the meantime, people needing medical care

had to be taken to a distant town.

Japan evaluates and posts building conditions using a red/yellow/green placard system very similar to the ATC-20 system used in the United States. The City of Sendai had completed safety evaluations of over 85% of their 8,900 buildings within three-and-a-half weeks after the earthquake. On April 7, a large aftershock (M7.2) required the evaluations to be started over. Building evaluations were completed two months after the March 11 main shock. 17% of the buildings were red-tagged (unsafe to enter).

Debris management was the highest priority at the time of the team visit. Vast quantities of building materials (mostly wood from residences), personal belongings, cars, and mud/sand had to be removed from sites and piled up so that reconstruction and other aspects of recovery could begin. Government officials had not yet decided on the final disposition of the debris at the time of the team's visit.

Recovery

The Sendai Airport was initially closed after the earthquake due to tsunami damage to the main terminal and airport infrastructure. At the time of the team's visit, the airport was operating at 20% capacity, and an aggressive reconstruction plan was under way. Full service was restored on July 25, 2011, four months after the earthquake and tsunami.

Restoration of utilities to coastal areas was a high priority but as late as three months after the event, electricity had not been restored in some areas.

Urayasu City (Tokyo metropolitan area) was built on fill and suffered extensive damage to utilities from liquefaction and subsidence. Temporary systems were in place at the time of the team visit, but city officials estimated it would take five to six years for complete restoration of utilities.

At the time of the team's visit, Japan was adjusting to a national reduction in electrical generating capacity, due to failure of the Fukushima nuclear power plant. The Tokyo Electrical Power Company produced graphs showing power consumption versus available capacity, which were displayed and updated in near-real time in public messaging outlets such as screens on trains.

Although some people who lost their homes moved in with relatives or friends in other parts of the country, Japan is faced with the need to provide temporary housing to replace many of the 100,000 homes destroyed by the tsunamis. In Miyagi Prefecture alone, 23,000 housing units were needed. At the time of the team reconnaissance (ten weeks after the event) 15,000 units had been constructed, but only half had been turned over to occupants.

Communities were making plans for rebuilding, but decisions on what and where to rebuild were still being made at the time of the team reconnaissance. Cash-strapped local governments needed help from an equally cash-strapped national government to implement any rebuilding plans. As expected, the planning process is taking time. In Miyagi Prefecture, draft rebuilding plans were expected to be submitted to the Prefecture Assembly for review and approval by late summer 2011.

General Observations

As Pacific Northwest officials and government agencies make plans for disaster response and recovery, they should focus on several lessons the Great East Japan earthquake has demonstrated. First, recovery efforts will need to focus on debris management and restoration of utilities. Second, in the aftermath of a major earthquake, communities can only achieve rapid recovery if the both commercial and residential recovery needs are carefully balanced. Finally, making temporary housing quickly available will reduce the burden on social services and decrease the stress on victims who are initially housed in emergency shelters.

CONCLUSIONS

Japan is the most prepared country in the world for earthquakes and tsunamis. The Great East Japan earthquake exemplifies how earthquake planning and preparedness can save lives and property, preventing an even greater disaster.

Seismic retrofit and protection technologies are effective at preventing earthquake damage. Japan has been quick to implement lessons learned from past earthquakes by updating building codes, and implementing protection technologies. These technologies (e.g., seismic base isolation and structural damping systems) are widely used in new construction and retrofits in Japan, not only in essential facilities, but also in single and multi-family housing, commercial buildings, and industrial facilities.

Most retrofitted buildings performed well during this earthquake with respect to both life safety and overall damage control.

The Japanese public and government officials expect enhanced seismic performance of buildings and facilities, and they understand the value of protecting people, buildings, and infrastructure from frequent, strong earthquakes. This M9.0 earthquake serves as a reminder that the life-safety performance of structures and infrastructure is not enough to create earthquake-resilient communities. Higher earthquake performance levels are also required to permit continuously habitable communities and promote rapid economic recovery.

Current U.S. building codes and standards for earthquake design of new structures are very good at providing life safety performance, but can be improved with respect to preservation of building functionality.

The Japanese government encourages private sector support of earthquake and tsunami research and development. This has resulted in widespread application of earthquake protection technologies in constructed projects.

Earthquakes around the world provide a real-world laboratory that teaches engineers, architects, and public officials how infrastructure and communities will perform in earthquakes. We must heed the lessons learned from these disasters.

Geologic studies along the Pacific Northwest Coast indicate that multiple earthquakes have occurred in the last 3,500 years. The most recent of these events occurred in the year 1700. An earthquake similar to the Great East Japan Earthquake will occur again along the Cascadia Subduction Zone. The impacts of this event on our communities and industry will depend on the actions we take now to prepare for it. The lessons learned from the Great East Japan earthquake can and should be applied in our own communities.

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