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LESSONS FOR CALTRANS FROM THE 2011 GREAT EAST JAPAN EARTHQUAKE AND TSUNAMI

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ABSTRACT: The M9.0 East Japan earthquake impacted a large area of Japan, but ground shaking severely damaged only a few bridges. The tsunami waves were high, but major bridge damage was due to girders that were picked up by the waves. Bridges that were well designed for ground shaking had little tsunami damage. However, moderate ground shaking damage closed bridges and impeded evacuation before the tsunami. Scoured embankments and debris-covered roads impeded the emergency response, delayed timely repairs to the nuclear power plants, and slowed the economic recovery.

Key Words: Tohoku earthquake, earthquake engineering, tsunami, roads, bridges, highway structures

INTRODUCTION

Caltrans Office of Earthquake Engineering investigates road and bridge damage after large earthquakes to see if any changes are required to the current seismic criteria. I went to Japan as part of a team from the American Society of Civil Engineers (ASCE) Technical Council on Lifeline Earthquake Engineering from June 12th to June 23rd in order to study the effects of the earthquake and tsunami on roads and bridges close to the northeast coast of Japan (Fig. 1).

Fig. 1 The ASCE (and JSCE) earthquake investigation team in Sendai

THE EARTHQUAKE AND TSUNAMI

The March 11, 2011 Tohoku earthquake was caused by thrust faulting on the subduction zone between the Pacific and North American plates (see Figure 2). Modeling of the rupture indicates the fault moved up about 30-40 m and slipped over an area about 300 km long by 150 km wide. The resulting tsunami waves exceeded 15 m in height and penetrated several km inland (Figure 3).

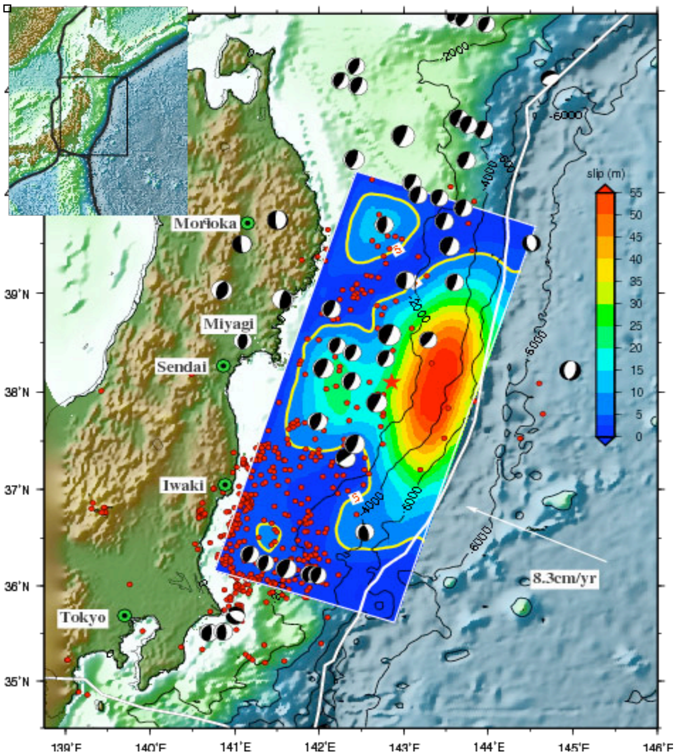

Fig. 2 Fault rupture map (USGS)

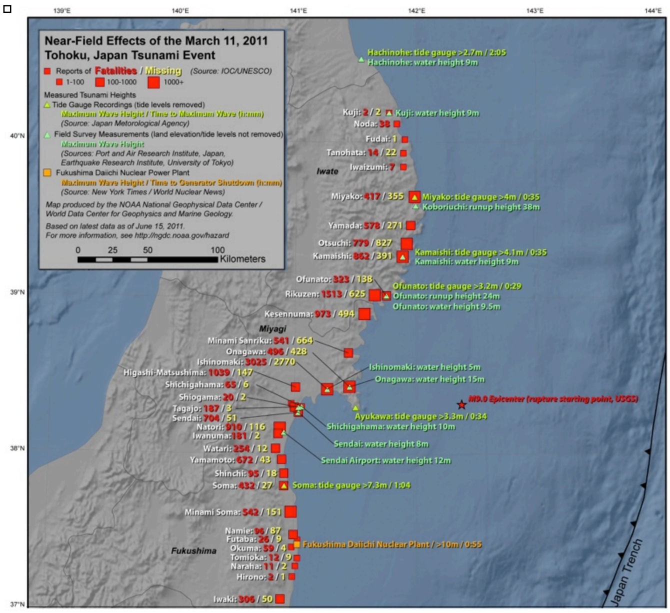

Fig. 3 Tsunami inundation map (NOAA)

TSUNAMI DAMAGE TO BRIDGES

Most bridges suffered little or no damage from the tsunami that accompanied the Tohoku earthquake. This was despite bridges not being specifically designed for tsunami. The lack of damage was often surprising. In the City of Miyako in Iwate Prefecture a video showed boats smashing into bridges (http://www.bbc.co.uk/news/world-asia-pacific-12725646).

An examination of these bridges after the earthquake revealed only minor damage. None of the columns were damaged despite having been struck by a several boats (Fig. 4). This good performance was due to the columns having been previously retrofitted with steel casings.

Fig. 4 During the tsunami several boats struck the Miyako Bridge (NILIM, 2011)

In contrast to the good performance of bridge columns on the Miyako Bridge, in Otsuchi not only was the superstructure on a railway bridge washed away but one of the columns was knocked over (Fig. 5). If this bridge had the proper development of its reinforcement and good confinement, then the column most likely would have remained standing.

Fig. 5 Undamaged and damaged columns on railway bridge in Otsuchi (Robertson, 2011)

Even when a tsunami wave overtopped a bridge it often remained undamaged. For instance, there were several bridges (Fig. 6) in Ohamawatari along Iyoushi Bay (near a damaged seawall) that were covered in debris due to tsunami inundation. However they suffered only minor damage. Moreover, these bridges were not especially well designed for lateral loads. They were precast girder bridges sitting on seat-type abutments and hammerhead bent caps. We saw this in many other locations.

Fig. 6 Bridge across river in Ohamawatari was covered with debris but undamaged (NILIM, 2011)

Another bridge-related problem was scouring of abutment backfills (Fig. 7). It didn't appear that one kind of embankment cover was more effective than another. Rip-rap, masonry blocks, asphalt and Portland cement concrete were all removed along with the embankments by the tsunami waves. In fact, tetra-pods (a registered trademark and also a generic term that refers to concrete blocks with several legs arranged along the shore to stop waves), other energy-dissipating systems, and even forests along seaside communities were all removed by tsunami waves. Scouring of the soil behind abutments was the most common type of bridge damage observed during the tsunami.

Fig. 7 Embankment scour at Kawaharagawa and Katagishi Bridges along Route 45 (NILIM, 2011)

Tsunami waves also scour riverbeds. Sediments are removed on the downstream side of obstacles and are deposited on the upstream side of the next obstacle. There were locations of pier damage that looked to be caused by scouring of the foundations. For instance, in Motoyoshi-cho there were two bridges that lost piers. In Fig. 8, we can see that Pier #3 of the Koizumi Bridge (in the center of the river) is missing. A little upstream is a bridge carrying the JR Kesen-Numa line (Figure 9) with several piers overturned in a manner suggesting the foundations were not well constructed. However, railway bridges generally weren't as well constructed as highway bridges and both of these bridges could have had pier damage due to ground shaking or due to the tsunami waves, which were particularly violent at this location.

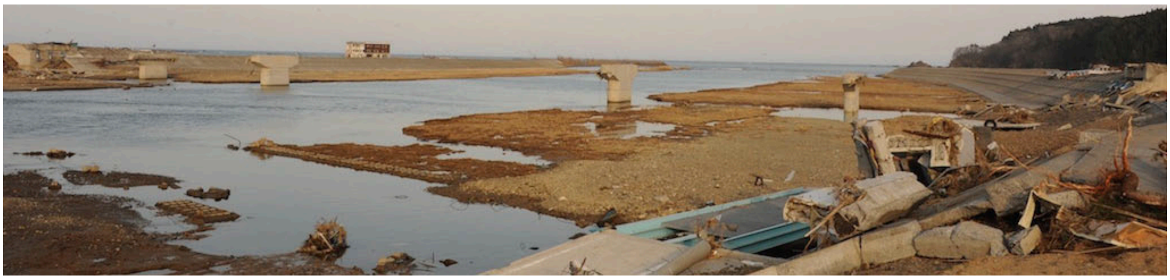

Fig. 8 Damage to Koizumi Bridge due to the tsunami (Kawashima, 2011).

Fig. 9 Damage to JR Kesen-Numa Bridge just upstream from the Koizumi Bridge (Kawashima, 2011)

Similar to embankments, roads in Japan were also vulnerable to tsunami. We saw pavement removed from roads on fill and at grade. Roads above the ocean were vulnerable and so were roads behind overtopped seawalls.

We still have a lot to learn about how a tsunami impacts roads and bridges. After the 2004 Sumatra Tsunami, Parsons had the job of quickly replacing roads along the shore near Aceh. They said one of the biggest challenges was determining what the shoreline would look like a year after the tsunami. They couldn't tell where sand removed during the tsunami would eventually be returned.

In Japan, we listened to talks by the Ministry of Transportation, by the National Expressway Corporation, and by the prefectural and local governments. They all said the major issue after the tsunami was clearing all the debris off the roads. The bridge damage was a further detriment since Highway 45 was the only route along the coast.

The Ministry of Land, Infrastructure, and Transportation (MLIT) was put in charge of the recovery for the first 20 days after the tsunami. They praised an emergency action plan (similar to Caltrans) that allowed them to hire contractors without competitive bidding to quickly remove debris from the roadways. Highway 45 was praised as being the one seawall that was effective at stopping the tsunami (see Fig. 10).

The relationship between ground shaking and the subsequent tsunami needs to be better explored. Because the rupture occurred near the coast, the tsunami arrived less than an hour after the ground shaking. Were bridges damaged by ground shaking more vulnerable to the subsequent tsunami? Were any bridge piers that were weakened by ground shaking later demolished by the tsunami? Were any people unable to evacuate before the tsunami due to bridge damage? Such an event could have occurred since an inland waterway, crossed by many bridges, was created along Japan's Pacific Coast hundreds of years ago as a protection for shipping.

Figure 10. The embankment supporting Route 45 was the barrier that stopped the tsunami (TV Asahi)

The tsunami is a complicated hazard. Waves carry large objects with a tremendous inertial force that destroys everything in their path. Smaller objects like cars and fishing boats caused less bridge damage. The impact of the wave, the forces as the wave moves around objects, the buoyant force from trapped air between the girders, and the hydrostatic force all play a role in road and bridge damage.

The idea that a bridge designed for strong ground shaking will perform well for a tsunami may not hold true when it comes to restraining the superstructure. There were many examples where cable restrainers, damping devices, and steel brackets snapped in two as girders pulled away from the piers and abutments (Fig. 11). However, the restraints didn't seem designed to resist large forces. Are tsunami forces higher or lower than the forces caused by ground shaking? We might not want to design restrainers for such a large force that they end up damaging the substructure. It may be better to let the girders float away and quickly replace them than to damage the substructure and end up building a new bridge after the tsunami.

Fig. 11 Broken brackets and restrainers on Utatsu Hashi and Yokozu Kyo Bridges (NILIM, 2011)

Bridge damage is related to various bridge parameters and also to the tsunami parameters at each bridge site. This includes the tsunami height, the tsunami wave force, uplift tsunami wave forces as well as structural characteristics such as span, height, weight of the girders, type of barrier rail, bearing strength, types of restrainers and shear keys, foundation characteristics, etc. It requires high, fast tsunami waves and a poorly detailed bridge to cause serious tsunami damage. If there is air trapped under the deck the tsunami can more easily pick up the girders and carry them away. Putting holes in the deck was considered as a way to remove the air between the girders during a tsunami, but it was found to be ineffective. If the girders are fixed to the piers, it may prevent the girders from floating away or it may cause pier damage, which may be costlier to repair.

Are waves that carry a lot of debris more destructive to bridges? Can the returning wave be more destructive? Are monolithic bridges safer than bridge girders sitting on drop bent caps? Does ground shaking weaken bridges that later collapse due to the tsunami? Some of these questions can be resolved by research currently being funded by Caltrans. Other questions may be addressed through physical testing. Some questions may be answered by carefully studying the bridge damage from this and other tsunamis.

GROUND SHAKING DAMAGE

One of Caltrans concerns is the high level of ground shaking recorded during this earthquake. One instrument (MYG004) recorded PGA of 2.5g and a spectral acceleration (at 0.24 seconds) of 12.9g (Figure 12). The site was 81 km from the rupture and had a shear wave velocity of 500 m/s. Caltrans designs bridges for PGA less than 1.0g and spectral acceleration generally less than 2g.

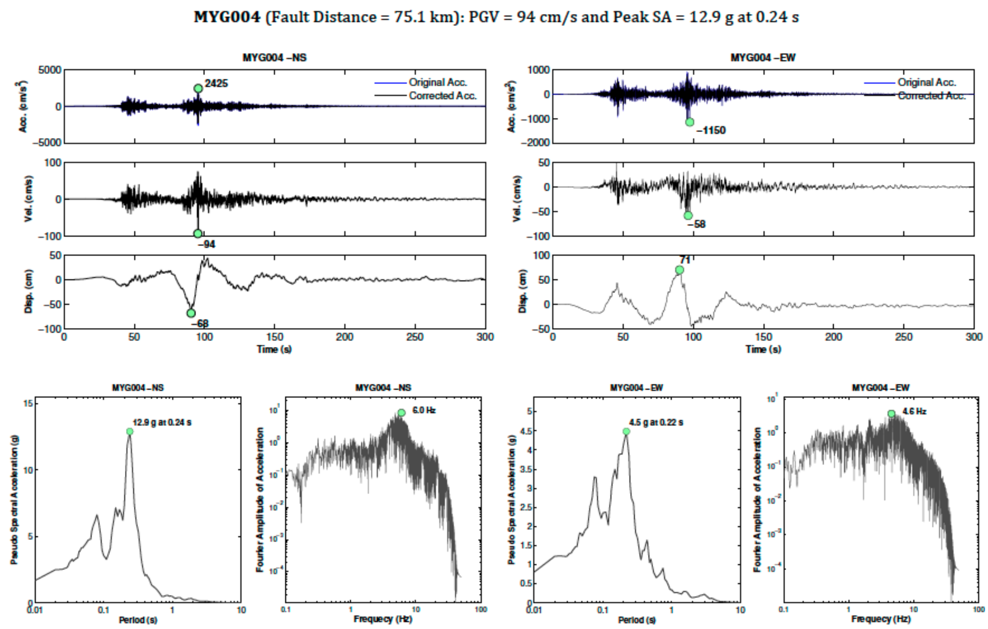

Fig. 12 Time history and response spectra recorded at instrument MYG004 during the Tohoku EQ

However, There was no bridge (or building) damage in Tsukidate (where the recording was made) according to Prof. Ikuo Towhata [5], a well-known geotechnical engineering professor at the University of Tokyo. Moreover, the recording shows a sharp spike in the recording suggesting there was some banging near the instrument. Most likely this recording is an outlier of the data and can be safely ignored.

There was less bridge damage due to ground shaking during the Tohoku earthquake than from the 1995 M6.9 Kobe earthquake. Strong ground shaking is expected close to the fault rather than 81 km away. Only a few bridges collapsed due to ground shaking and this was often the result of liquefaction and lateral spreading. For instance, the Rokko Bridge had settlement of the approaches and the loss of two piers and three spans (Fig. 13). This is similar to the damage that occurred to the Showa Bridge during the 1964 Niigata earthquake and probably had the same cause, loss of strength and stiffness of the surrounding soil due to liquefaction.

Fig. 13 Damage to Rokko Bridge in Ibaraki Prefecture

There was a lot of damage to truss bridges due to buckled cross bracing, broken bearings and expansion joint devices, and torn and buckled gusset plates. An interesting example of this type of damage occurred to the Kosoku-Arakawa Truss Bay Shore Bridge (built in 1978) just north of Tokyo Bay. As shown in Fig. 14 below, the bridge is an 840 m long, seven span truss bridge with a drop-in steel girder center span. The truss elements are held together with gusset plates that were too thin for the seismic forces. About twenty plates buckled in compression or were torn apart in tension (usually both) as shown in Fig. 15. Gusset plates should be capacity-protected members and stronger than the members they connect. Fortunately, the bridge did not fall apart and the Metropolitan Expressway Corporation was able to replace all the damaged gusset plates.

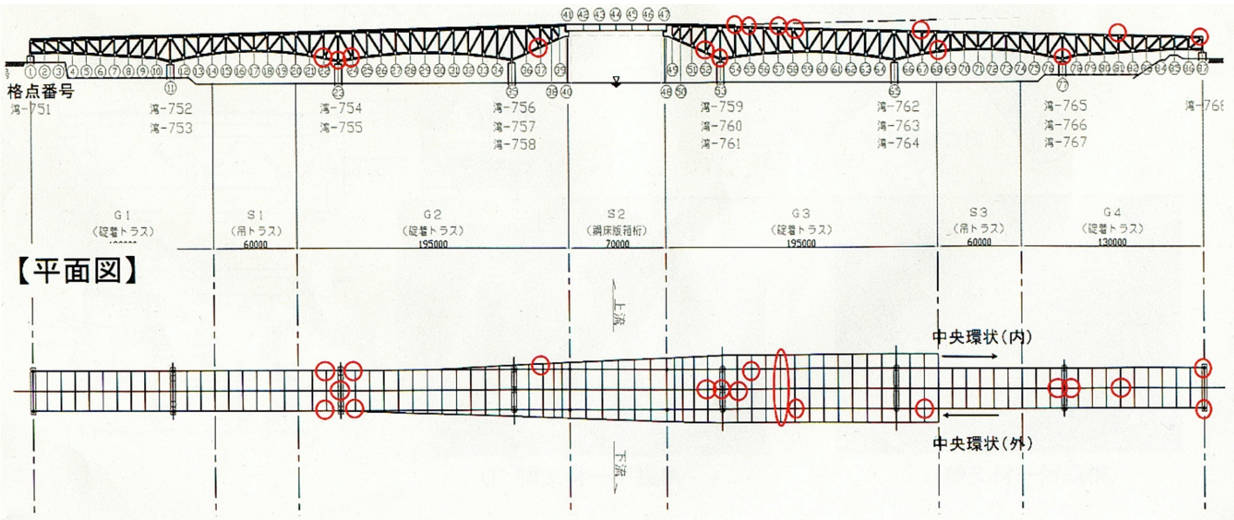

Fig. 14 Drawing of the Kosoku-Arakawa Bridge showing locations of gusset plate damage

Fig. 15 Gusset plate damage for horizontal and vertical members

PERFORMANCE OF HIGH-SPEED RAIL

The Shinkansen (bullet train) travels on a network of about 1400 km of standard gauge track from the bottom of Kyushu to the top of Honshu. Despite being well designed and modern in many ways, the trains ride on viaducts (to avoid traffic delays) that are too stiff and have poor reinforcement details. After every earthquake (1995 Kobe, 2003 Miyagi Oki, 2004 Niigata, 2011 Tohoku) the damaged viaducts are repaired and retrofitted, but a rigorous retrofit program hasn't occurred. No lives have been lost partly because of the excellent safety system, the Urgent Earthquake Detection and Alarm System (UrEDAS) that quickly stops all the trains whenever an earthquake occurs. High speed rail might work better travelling slightly below grade like the Alameda Corridor in Los Angeles.

During the Tohoku earthquake, viaducts were damaged in Koriyama (Fukushima Prefecture), in Sendai (Miyagi Prefecture) and in Kitakami, Hanamaki, and Morioka (Iwate Prefecture) as shown in Fig. 16.

Fig. 16 Map of Shinkansen with locations of damage during earthquake

A very typical example of the damage to the Tohoku Shinkansen Line is shown in Fig. 17 on the Hanimaki Viaduct in Sendai. This viaduct is composed of four span frames with drop-in spans between the frames. The end bents are shorter and stiffer to carry the drop-caps which support the drop-in spans. Almost all the damage to the Shinkansen Line were to the stiffer columns on the end bents (There was also a lot of damage to transverse beans used to stiffen tall bents.

Fig. 17 Damage to Shinkansen Viaducts in Hanamaki

Demand for the Shinkansen is very high in Japan. Domestic flights around Japan are low because most urban areas are accessible in a few hours by Shinkansen. All seats are reserved, the trains leave every hour, and it is an extremely reliable form of transportation. Because no revenue was coming in to JR East due to damage to the viaducts, all the damage was repaired in a few weeks. Unfortunately, many of the repairs were damaged again by large aftershocks that continued for several months after the earthquake.

LESSONS LEARNED

Lesson 1: Bridges that were retrofit for ground shaking generally remained in service following the tsunami. However, the situation when the girders were overtopped needs further study.

Lesson 2: Bridges with poor seismic details (little confinement, inadequate development of reinforcement into adjacent members, etc.) performed poorly during the tsunami.

Lesson 3: Large velocity waves and/or poor connection details are necessary to uplift girders.

Lesson 4: Protecting embankments from tsunami-induced scour still needs to be studied.

Lesson 5: A determination of the scour vulnerability for bridge foundations requires wave height and velocity data as well as a set of bridge plans.

Lesson 6: As the tsunami wave overtops the seawall the water reaches critical velocity with increased destructiveness until the wall is inundated. As the water continues to rise the wall reduces the velocity of the tsunami wave until the water becomes too high for the wall to be effective (according to Prof. Solomon Yim at Oregon State University).

Lesson 7: Roadway embankments, a sufficient distance from the coast, make effective tsunami walls.

Lesson 8: Ground shaking followed by a tsunami needs to be studied for bridges along the coast.

Lesson 9: Ground shaking forces need to be compared to tsunami forces to determine if girders can be tied down to resist both hazards without severely damaging foundations and substructures.

Lesson 10: Need to determine implications of recorded ground motions well above current practice.

Lesson 11: High-speed rail may be safer below grade than on stiff viaducts with smaller ductility. Alternately, higher performance may be obtained using isolation bearings with fuses to allow the ground to shake while the deck has little movement.

Lesson 12: Owners and users of high-speed rail cannot wait several months after large earthquakes for aftershocks to subside. The line should be designed to be quickly repaired after large earthquakes and to remain in service for smaller earthquakes.

CONCLUSIONS

There are many lessons that we can learn about the behavior of bridges impacted by tsunami waves. Some of the concerns about potential bridge vulnerabilities will be addressed by the analytical studies currently being conducted at Oregon State University under a contract with Caltrans. Other issues may be addressed through physical testing using the tsunami wave generator. However, it would also be useful if parameters of the bridges in the tsunami inundation area were put in a database and studied to identify those parameters that were significant for bridges standing and bridges collapsing. From observations made during this event we saw that bridges retrofitted or designed for ground shaking usually performed very well for tsunami. More research is needed to see if our current seismic design provides adequate protection from tsunami forces. The vulnerability of the embankments to tsunami waves is problematic and may require testing to see how they can be protected. It seems that monolithic bridges performed better than precast or steel girder bridges because they don’t have elements that can be picked up and carried away.

Another issue is the very strong ground shaking that was recorded during this earthquake. There didn’t seem to be enough damage to suggest that PGA had been over 3.0g with significant amplifications at longer periods. Moreover, these recordings were at large distances from the fault rupture. Changes to attenuation relationships should be studied after each well-recorded earthquake.

Most of the ground shaking damage was due to lack of uniformity between elements, which caused the weaker elements to fail. There was also soil problems that led to fatalities and bridge collapses. Some steel trusses performed poorly due to inadequate connections.

Finally, the idea of supporting high-speed rail on stiff viaducts needs to be re-examined. The Shinkansen was put above grade to prevent delays and possible collisions but these viaducts are designed to be stiff (to support trains travelling 200 mph) and they are vulnerable to earthquakes. It might be better to put high-speed rail underground or on isolation devices so they can be quickly repaired for large earthquakes and remain in service for smaller earthquakes.

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