U.S.-Japan Joint Reconnaissance Report of Bridge Damage due to 2011 Tohoku Earthquake

by

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ABSTRACT

Task committee G (Transportation) of the Panel of Wind and Seismic Effect, UJNR conducted the U.S-Japan joint reconnaissance of bridge damage due to the 2011 Great East Japan Earthquake in June, 2011. Thirteen experts participated in this reconnaissance from both Japan-side and U.S.-side, and the reconnaissance team investigated 11 highway bridges in Tohoku and Kanto areas.

This paper summarizes the preliminary findings of the reconnaissance and lessons learned from the earthquake based on the joint reconnaissance.

KEYWORDS: 2011 Great East Japan Earthquake, Highway Bridges, Tsunami Effect, Seismic Retrofit, Long Duration

1. INTRODUCTION

The 2011 Great East Japan Earthquake occurred at 2:46 pm on March 11, 2011. The catastrophic damages resulting from strong ground motion and huge tsunami remain in Tohoku and Kanto regions. More than 20,000 people were killed or missing, and various infrastructures were damaged, especially in the coastal area of Iwate, Miyagi, Fukushima and Ibaraki Prefectures.

Many highway bridges were also damaged in these areas due to both large ground motion and tsunami effects. Soon after the earthquake occurred, NILIM and CAESAR in PWRI jointly investigated bridge damage conditions and provided the technical supports and suggestions to bridge administrators, including Regional Bureaus of MLIT and Local Governments. Based on the primary investigation conducted by NILIM and CAESAR, Task Committee G conducted the U.S.-Japan joint reconnaissance to bridge damage during June 3 to 6, 2011. The joint reconnaissance focused on following points; damaged bridges due to tsunami or strong ground motion effects, verification of seismic performance of bridges retrofitted after the 1995 Hyogo-ken Nambu earthquake, validations of effectiveness of the current seismic design specification policy.

2. OUTLINE OF EARTHQUAKES AND BRIDGE DAMAGE

2.1 Outline of Earthquakes

The main shock of this earthquake (Mw=9.0, focal depth=24km) occurred at 2:46 pm (JST) on March 11, 2011. Maximum seismic intensity was observed at Tsukidate, Kurihara city in Miyagi prefecture (Seismic intensity of JMA was 7) and large seismic intensities were observed in Tohoku and Kanto areas.

Figure 1 shows acceleration ground motion waveforms and spectral response accelerations at representative strong ground motion observation sites.

It should be noted that 1) strong ground motion records with long duration were observed and 2) there were multiple pulses in some ground motion records observed near epicenter. This is because large fault areas collapsed continuously. It was observed at very large maximum response acceleration at the range of short predominant period such as Tsukidate record. The maximum response accelerations at the range of natural periods from 1.0 to 2.0 seconds, which relatively correlate with damage of ordinary road bridges, were equal or slightly less than those of the 1995 Hyogo-ken Nambu earthquake. Ground motions and maximum response accelerations at the coastal area of Tohoku region were not so large. However, strong ground motions and large
response accelerations were observed at the sites where located slightly far from epicenter such as Fukushima, Tochigi and Ibaraki prefectures.

Huge tsunami induced by main shock struck at Tohoku and Kanto coastal areas and exceeding 10m in height of wave were observed.

Moreover, aftershocks with the JMA magnitude of 7.0 or over were occurred three times within a day and total of 89 aftershocks with the magnitude of 6.0 or over were occurred until August 3.

Additionally, large earthquakes induced by Tohoku earthquake were occurred at far site from fault area of Tohoku earthquake such as Nagano Prefecture (March 12, $M_{\text{JMA}}=6.7$ (tentative)) and Sizuoka Prefecture (March 15, $M_{\text{JMA}}=6.4$ (tentative)).

2.2 Outline of Bridge Damage
Damage of the highway bridges due to this earthquake can be categorized as follows:
- Effect of tsunami,
- Effect of strong ground motion, and
- Effect of soil liquefaction

Many highway bridges were damaged by tsunami. Twelve bridges including service road for pedestrian were washed away on national highway route 45, which was main route along the Pacific coast of Tohoku Area. Total of about 80 highway bridges were fallen down due to tsunami in Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures. The backfill of abutment in some bridges were washed out even though girders and substructures were survived.

Rokko Ohashi Bridge, a steel girder bridge supported by steel pile-bent columns located in Ibaraki prefecture, was collapsed by the effects of strong ground motion. It was also found that damage to RC columns at section of cut-off of longitudinal rebars, damage to RC pier-wall with small amount of reinforcement, damage to steel bearings and attachment of bearings, damage to bracing and steel members, and subsidence of backfill soil of abutment. It should be noted that elastomeric rubber bearings were ruptured at the Sendai-Tohbu viaduct designed based on Post-Kobe Earthquake specification.

Because of subsidence of backfill soil of abutment due to the soil liquefaction effect, deck-end gap was shortened resulting from movement of substructure, which caused steel bearings damage and parapet wall cracks.

The typical damages were shown in Figure 2.

3. JOINT RECONNAISSANCE OF BRIDGES
A joint reconnaissance team of highway bridges was organized and perform the post-earthquake investigation during June 3rd to 6th. Seven Japanese and six U.S. experts participated in the team. Both sides' members were as follows,

Japan side;
Tetsurou Kuwabara, TC/G chair, PWRI
Kazuhiko Kawashima, Tokyo Institute of Tech.
Keiichi Tamura, PWRI
Shigeki Unjoh, NILIM
Jun-ichi Hoshikuma, PWRI
Taku Hanai, PWRI
Hideaki Nishida, PWRI

U.S. side;
W. Phillip Yen, TC/G chair, FHWA
Ian Buckle, University of Nevada Reno
David Frost, Georgia Institute of Tech.
Shideh Dashti, University of Colorado
Eric Monzon, University of Nevada, Reno
Lee Marsh, Berger/ABAM Engineers

Total of 11 highway bridges were investigated at Tohoku and Kanto regions; 4 bridges damaged by tsunami, 5 bridges damaged by strong ground motion and 2 retrofitted bridges.

Table 1 lists the bridges that the team investigated, and Figure 3 shows the location map of the bridges except Arakawa Wangan Bridge (because it is located in Tokyo.). Additionally, the team investigated other infrastructure damaged due to liquefaction at Urayasu area in Chiba Prefecture.

3.1 Bridge Damaged by Tsunami
The team investigated four damaged bridges
due to tsunami, which were located at Kesennuma city and Minami-Sanriku Town in North part of Miyagi prefecture.

3.1.1 Koizumi Ohashi Bridge (see Figure 4)
This bridge was a 6-span steel girder bridge (two three-span-continuous girders) across Tsuya River. Substructure consisted of RC pier walls with steel pipe piles. The pier walls have been retrofitted by wrapping up with FRP sheets for P2 and P4; and installing dampers between abutment and girder. The height of Tsunami was estimated exceeding 10 meter high in this area. All girders and one RC pier-wall (P3) were washed away to the upstream direction. The girders were rested about 450m far from original position.

P3 pier-wall, originally supported two girders with movable bearing support, was found about 50m away from original position. This pier was broken at the bottom (top of footing). The possible reason for only P3 being washed away was due to the ultimate strength of the pier-wall was weaker than the other piers.

Moreover, backfill soil of abutment was also washed out at both sides.

A railroad bridge located about 1km far from Koizumi Ohashi Bridge to upstream direction of Tsuya river was also collapsed. Girders were washed away and RC columns were leaned to upstream directions.

3.1.2 Sodeogawa Bridge (see Figure 5)
Sodeogawa Bridge is a 4-span RC hollow slab bridge located next to Koizumi Ohashi Bridge.

This bridge was not washed away except for the upstream side 3 girders of service road for pedestrian. Moreover, one of two-span-continuous box culvert with downstream side of service road for pedestrian was leaned by unequal settlement of supporting layer. Backfill soil was washed out at Koizumi Ohashi side.

3.1.3 Nijyuichihama Bridge (see Figure 6)
Nijyuichihama Bridge is a single-span PC hollow slab bridge. This bridge was not washed away except the seaside girder of service road for pedestrian. However, traffic could not be opened after the earthquake because backfill soil of abutment was washed out at both sides. It was found that the steel pile head of abutment exposed by scouring due to tsunami.

At the time the team visited, temporary repair work had been finished and temporary steel girders were set at the part of backfill soil.

3.1.4 Utatsu Ohashi Bridge (see Figure 7)
Utatsu Ohashi Bridge is a 12-span PC single girder bridge. Piers consisted of circular RC column (P1 and P2) and rectangular RC column with PC piles. Bridge columns have been retrofitted by RC jacketing and an extension for the seat length was installed at the top of pier. Total of 8 spans (from P2 to P10) were washed away to the inland direction. It was found that concrete and steel shear keys, installed at the pier beam, were damaged and some beams of inland side were cracked at the piers which girders were washed away as well. A lot of diagonal cracks were also observed at the bottom of main girders of some unseated girders.

At the top of column of P2, cover concrete of additional portion of concrete jacketing was spalled.

3.2 Bridge Damaged by Strong Ground Motion

Five damaged bridges due to strong ground motion were investigated.

3.2.1 Sendai-Tohbu Viaduct (see Figure 8)
Sendai-Tohbu Viaduct is designed in accordance with the 1996 seismic design specification revised soon after the 1995 Hyogo-ken Nambu Earthquake.

At the damaged part of bridge, it was a 4-span steel box girder (Pier No.52 to No.56) adjoining a 2-span steel girder (Pier No.56 to No.58).

It was found that elastometric rubber bearings at pier No.52, No. 54 No.56 and No.58 were ruptured and some of superstructures were separated from bearings. This section was closed about 3 weeks until temporary repair work was done. Some yielded members were repaired by adding stiffeners, and superstructures were reset.
at the original positions.

3.2.2 Ezaki Ohashi Bridge (see Figure 9)
Ezaki Ohashi Bridge is a 9-span continuous PC box girder bridge across Kitakami River. Substructure consisted of RC pier walls with caisson (P1 to P4) and spread footing (P5 to P8). Two damper stoppers were installed for each pier top to disperse seismic force.

Shear crack, spalling cover concrete and buckling of longitudinal rebars were found at the cut-off cross section of P5, P6, P7 and P8. The heights of these piers were lower than the other piers. At the time when the team visited, temporary repair work for piers had been finished by wrapping up with carbon fiber sheet.

3.2.3 Shida Bridge (see Figure 10)
Shida Bridge is a 9-span cantilever steel girder bridge across Naruse River. Spalling cover concrete at piers, settlement of backfill soil, and residual displacement by moving of superstructure was found.

3.2.4 Fuji Bridge (see Figure 11)
Fuji Bridge was a 13-span steel girder bridge across Kitakami River. It is interesting that this bridge was damaged due to not the main shock but the aftershock with magnitude of 7.1 occurred on April 7.
Shear crack, spalling concrete and buckling of longitudinal rebars were observed at the piers and the pin in the steel bearings was ruptured.

At the time when the team visited, temporary repair work for piers was done by wrapping up with carbon fiber sheet or PC cable confining method.

3.2.5 Arakawa Wangan Bridge (see Figure 12)
Arakawa Wangan Bridge is a 7-span cantilever truss bridge across Arakawa River. When main shock occurred, seismic retrofit works installing additional bracings were to start and scaffolding was built through the main truss member.
Total of 31 points such as connections between buttress strut and lateral bracing or cross frame were damaged. Temporary repair work had already done and traffic was opened when the team investigated.

It should be noted in this bridge that the scaffolding for the construction helps quick bridge inspection soon after the earthquake.

3.3 Verification of Seismic Retrofit of Bridges

The off Miyagi prefecture earthquake with JMA magnitude of 7.4 occurred in June 12, 1978. It should be interesting to compare the damage between the 1978 off Miyagi prefecture earthquake and the 2011 Great East Japan Earthquake. Following two bridges were damaged due to 1978 earthquake and then retrofitted after the earthquake.

3.3.1 Sendai Ohashi Bridge (see Figure 13)
Sendai Ohashi is a 9-span steel girder bridge across Hirose River. At the 1978 earthquake, piers were damaged by spalling cover concrete and buckling of longitudinal rebars, so that RC jacketing and resin grouting were done as repair work. Additionally, replace of bearing to rubber bearing, install the unseating protection systems and retrofit of pier by carbon fiber were done later.

No significant structural damage was found in this bridge due to the 2011 earthquake.

3.3.2 Yuriage Ohashi Bridge (see Figure 14)
Yuriage Ohashi Bridge is a 7-span with simple-supported PC girder, and 3-span simple-supported PC cantilever box girder bridge across Natori River. At the 1978 earthquake, columns were damaged with spalling cover concrete, shear crack at web of PC girder near bearing, moving to roller bearing, so that RC jacketing and resin grouting were done as repair work.

These retrofitted columns in Yuriage Ohashi Bridge were no damage during this earthquake, however damage of bearing supports and cracking at the end of PC girder were observed. It should be noted that tsunami attached Yuriage Ohashi Bridge after the earthquake. However the effect of tsunami on the damage of Yuriage Bridge was unclear, since tsunami height at this site was uncertain.

4. IMPACT OF 2011 GREAT EAST JAPAN EARTHQUAKE ON SEISMIC DESIGN OF HIGHWAY BRIDGES
The seismic performance of highway bridges, designed in accordance with the post-Kobe Japanese specifications, was very well and these bridges were functional without any long-term traffic stops after the earthquake. However, there are several important issues and lessons we should study and review for the latest seismic design specifications for highway bridges. Followings are the selected issues.

4.1 Ground Motion

4.1.1 Effect of Long Duration Earthquake on Seismic Performance of Bridges

In the 2011 Great East Japan Earthquake, many strong ground motion records were recorded and these records clearly showed that this earthquake generated ground motions with multiple pulses and thus the longer duration (more than 2 minutes) than other records observed in the past earthquakes. Similar ground motions were reported in the 2010 Chile Earthquake with the moment magnitude Mw 8.8. Therefore, the subduction-type earthquake with Mw of nearly 9 may induce the ground motion with long duration.

In general, the long duration would affect the number of cyclic inelastic response of the bridge system. Past experimental researches indicated that the loading pattern in the quasi-static cyclic loading test, particularly the number of cyclic loading affects the ductility capacity of flexural reinforced concrete column. In order to accommodate such effect into the seismic design, Japanese design specifications have determined two ductility/shear capacity factors based on the types of the ground motion, i.e. the subduction-type and the near-fault-type. Re-studies on the effect of the long duration will be required based on the ground motion observed in the 2011 Great East Japan Earthquake.

The long duration would also affect the soil liquefaction. Effect of the soil liquefaction on the seismic design of bridge foundation was introduced in the 1971 specifications in Japan based on the lessons learned from the 1964 Niigata Earthquake. Although there were no major liquefaction-induced damages in bridges during the 2011 Great East Japan Earthquake, the long duration effect on the bridge performance built on the liquefiable sandy soil condition should be verified through both geological and structural perspectives.

4.1.2 Properties of Ground Motion and Damage of Bridges

Since the ground motion effect propagated wide, bridge damage developed in wide area. Many ground motion records were also observed in wide area. It should be important to study the relation between the properties of the ground motion and damage of bridges.

4.2 Tsunami Effect on Bridges

Superstructures in several bridges were washed away due to the tsunami effect. Backfill soil for the abutment was also washed out. Similar damage modes in bridge were also observed during the 2004 Indian Ocean Earthquake. Failure mechanism of bridge system due to the tsunami effect need to be studied, in which the resistance capacity of the existing bearing supports be analyzed based on both the washed-away and survived bridges. Also, more experimental researches on the bridge behavior due to the tsunami effect are required, to find the appropriate structural system for mitigating the tsunami effect.

Bridge design with hold-down devices in preventing wind uplifting forces may be considered as one countermeasure in the tsunami area as the bridge failure scenarios may involve buoyancy forces from water. Restrainers installed for wind uplifting forces may also work in relative small tsunami.

On the other hand, the design concept of bridge for unexpected extraordinary event would be controversial, because structural resistance capacity has a limit. Basically, it would be one of the options for the extraordinary tsunami effect to avoid routing important highway network and locating important bridges in the tsunami-risk area. In terms of structural engineering, easy-to-
repair bridge system is also another option.

4.3 Validations of Effectiveness of Seismic Retrofit

Seismic retrofit have been performed step-by-step since 1995 Kobe earthquake. Based on the lessons learned from the past earthquakes, bridge columns in the important highway network designed by pre-1980 specifications have been retrofitted with high prioritization. Many seismic vulnerable bridges in the important route such as National Highway Route 4, 6, 45 etc were retrofitted up to the date of the earthquake, which resulted in quick recovery of the functional highway network after the earthquake. It should be important review to investigate details of minor damage in the retrofitted bridges and evaluate the seismic behavior of the bridge during the earthquake.

5. CONCLUDING REMARKS

Bridge seismic performance was very well under this huge devastated earthquake although some bridge spans were washed out by great tsunami impacting and other combination forces. There are many lessons learned from this unique earthquake, including long duration impact, tsunami effects. Bridges designed with newer design codes performed much better than those older one. The better we understand the bridge seismic characteristic response, the better we can improve our bridge seismic safety.

Earthquakes are inevitable hazards. However, the better we prepared for the earthquake hazard, the better we reduce the loss due to the earthquakes. Through the joint reconnaissance, the US and Japanese side shared the experience and technology developed, and work together to reduce the loss of earthquake hazards.

6. REFERENCES

Fig. 1 Acceleration Waveforms and Spectral Response Acceleration at Main Shock (NS comp.)
(a) Collapse of Bridge with Pile-bent Columns

(b) Damage to RC Pier Wall with Small Amount of Reinforcement

(c) Damage to Pier Top

(d) Subsidence of Deck-End Resulting from Broken Movable Bearing

(e) Slight Buckling and Crack Observed in Lower Chord Member

Fig. 2(1) Typical Bridge Damages (by Effect of Strong Ground Motion)
(a) Shortened Deck-end Gap Resulting from Movement of Abutment

(b) Subsidence of Soil

(c) Subsidence of Backfill soil of Abutment

Fig. 2(2) Typical Bridge Damages (by Effect of Soil Liquefaction)

Table 1 List of Investigation Bridges

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of Bridge</th>
<th>Const. year</th>
<th>Length (m)</th>
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<tr>
<td>1</td>
<td>Sendai-Tohbu viaduct</td>
<td>2000</td>
<td>4390</td>
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<td>Koizumi Ohashi Br.</td>
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<tr>
<td>3</td>
<td>Sodeogawa Br.</td>
<td>1972</td>
<td>60</td>
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<td>4</td>
<td>Nijyuichihama Br.</td>
<td>1971</td>
<td>16.64</td>
</tr>
<tr>
<td>5</td>
<td>Utatsu Ohashi Br.</td>
<td>1972</td>
<td>303.6</td>
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<tr>
<td>6</td>
<td>Shida Br.</td>
<td>1958</td>
<td>266</td>
</tr>
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<td>7</td>
<td>Sendai Ohashi Br.</td>
<td>1965</td>
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<tr>
<td>8</td>
<td>Yuriage Ohashi Br.</td>
<td>1974</td>
<td>541.7</td>
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<td>9</td>
<td>Ezaki Ohashi Br.</td>
<td>1982</td>
<td>586.2</td>
</tr>
<tr>
<td>10</td>
<td>Fuji Br.</td>
<td>1972</td>
<td>705</td>
</tr>
<tr>
<td>11</td>
<td>Arakawa Wangan Br. (Tokyo)</td>
<td>1978</td>
<td>840</td>
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</table>

Fig. 3 Locations of Investigation Bridges
Fig. 4(1) Koizumi Ohashi Br. (March 15)

Fig. 4(2) Wash Away of Steel Girder of Koizumi Ohashi Br. (June 4)

Fig. 4(3) Collapsed Railway Bridge Columns near Koizumi Ohashi Br. (June 4)

Fig. 5 Sodeogawa Br. (June 4)

Fig. 6(1) Nijyuichihama Br. (March 15)

Fig. 6(2) Nijyuichihama Br. (Before earthquake, provided from Tohoku Regional Development Bureau, MLIT)
Fig. 6(3)  Nijyuichihama Br. (April 9, provided from Tohoku Regional Development Bureau, MLIT)

Fig. 6(4)  Nijyuichihama Br. (June 4)

Fig. 7(1)  Utatsu Ohashi Br. (June 4)

Fig. 7(2)  Utatsu Ohashi Br. (June 4)

Fig. 7(3)  Utatsu Ohashi Br. (March 19, provided from Tohoku Regional Development Bureau, MLIT)
Fig. 8.1 Sendai-Tohbu Viaduct (June 3)

Fig. 8.2 Sendai-Tohbu Viaduct (June 3)

Fig. 8.3 Rupture of Rubber Bearing on Pier No. 54 (April 6)

Fig. 8.4 Rupture of Rubber Bearing (April 6)

Fig. 9.1 Ezaki Ohashi Br. (April 6)

Fig. 9.2 Ezaki Ohashi Br. (June 5)

Fig. 9.3 Ezaki Ohashi Br. (June 5)

Fig. 10. Shida Br. (April 7)
Fig. 11(1) Fuji Br. (April 26)

Fig. 11(2) Fuji Br. (June 5)

Fig. 12(1) Arakawa Wangan Br. (June 6)

Fig. 12(2) Arakawa Wangan Br. (June 6)

Fig. 13 Sendai Ohashi Br. (June 5)

Fig. 14 Yuriage Ohashi Br. (June 5)