Lessons Learned from Bridge Performance of the 1999 Turkish &Taiwan Earthquakes

W. Phillip Yen[1], Hamid Ghasemi[1], and James D. Cooper[2]

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ABSTRACT

This paper presents preliminary findings concerning bridge performance and lessons learned from the three large earthquakes that struck Turkey and Taiwan in 1999. These findings seek to associate types of damage with fault types.

1. INTRODUCTION

In 1999, three major earthquakes struck Turkey and Taiwan. These temblors measured moment magnitude (Mw) 7.4 (Kocaeli, Turkey), Mw 7.6 (Chi-Chi, Taiwan) and Mw 7.2 (Duzce, Turkey) respectively, causing the loss of thousands of lives and severe infrastructure damage. Working with the Turkish and Taiwanese Departments of Transportation, Federal Highway Administration earthquake reconnaissance teams investigated the highway infrastructure damage and evaluated the bridges' performance under these strong ground motions.

Tunnels and bridges on the Trans-European Motorway (TEM) between Ankara and Istanbul, Turkey were carefully examined after the Kocaeli earthquake, the first of two in Turkey in 1999. One overpass (Arifiye) along the TEM collapsed due to a fault rupture passing directly beneath the north span. Poorly detailed and constructed shear keys were damaged in some bridges allowing large offsets of the bridge deck. The second earthquake (Duzce) damaged construction sites on the TEM in the Bolu area of Turkey. The Bolu Tunnel and a nearby viaduct (Viaduct #1) were severely damaged and scenarios for the cause of the damage were investigated. This paper only discusses Viaduct #1. The findings on Bolu Tunnel, which is explained in great detail, can be obtained from Reference 1.

The largest earthquake of the three in magnitude, the Chi-Chi earthquake, caused collapse of many highway bridges located in central Taiwan. More than 10 bridges, including a cable-stayed bridge, were severely damaged. Some bridges designed and constructed under modern bridge codes also suffered severe damage.

In general, bridge performance was studied in reference to near fault effects, shear key and bearing design, load paths, column-to-cap beam joints, and vertical acceleration effects. This paper presents the preliminary findings and lessons learned from the

[1] Office of Infrastructure R&D, Federal Highway Administration
6300 Georgetown Pike, McLean, VA 22101, USA
[2] Office of Bridge Technology, Federal Highway Administration
400 7th Street, SW, Washington, D.C. 20590

investigations of these three devastating earthquakes.

2. KOCAELI and BOLU EARTHQUAKES, TURKEY

In 1999, two severe earthquakes in Turkey caused 15,000 fatalities and over 30,000 injuries. There was extensive destruction to residential and commercial buildings, and to industrial facilities in many cities. In general, the bridges and tunnels located along the (TEM) performed much better than the buildings because of better QA/QC procedures. One overpass collapsed in Sakarya and one viaduct and tunnel in Bolu experienced extensive damage and partial collapse. The transverse shear keys in many bridges apparently were not designed, detailed, or constructed properly which resulted in large movements of the superstructure. Most of the damage sustained by bridges was the result of fault rupture at or near their sites.

<u>Kocaeli Earthquake:</u>
The first earthquake, the Kocaeli earthquake (Figure 1), occurred on August 17 and had a moment magnitude of 7.4 (Figure 1). It was caused by a right lateral strike-slip rupture along the main segment of the North Anatolian Fault (NAF) near the town of Golcuk, in the province of Kocaeli, which is located about 80 km east of Istanbul. The length of the surface fault rupture is estimated to be 150 km with an average lateral offset of 3-5 m along most of its length. There were many stations that recorded the ground motion during the earthquake, with values varying from 0.09g in Istanbul to 0.41g in Adapazari. The General Directory of Disaster Affairs operates these recording stations. The FHWA team inspected over 20 viaducts and tunnels along the TEM.
<u>Duzce Earthquake:</u>
The second earthquake with a moment magnitude of 7.2, the Duzce earthquake, occurred on November 12 along the secondary Duzce fault, a branch of the NAF. Its epicenter was centered near the town of Duzce, in Bolu Province, with a population of 80,000. This is approximately 140 km east of Golcuk, the epicenter of the earlier Kocaeli earthquake. The length of the strike-slip surface fault rupture is estimated to be 40 km with an average lateral offset of 4 m along most of its length. According to seismologists the rupture on November 12 resulted from the stress created by the Kocaeli earthquake.

At the Düzce station near the epicenter, Peak Ground Acceleration (PGA) of 1.0g was recorded before the ground motion instrumentation was clipped due to its limitation on recording acceleration above 1.0g. The instruments at Bolu, located 30 km east of the epicenter, registered a PGA of 0.8g. Between the two stations, in the towns of Kaynasli and Bolu, there are two viaducts (Viaducts #1 and #2) and one tunnel (Bolu Tunnel) under construction. Therefore, it is reasonable to assume that these structures, which were not instrumented, experienced a PGA in excess of 0.4g, their design value. These structures are part of the last 24-km segment of the TEM that is to be completed.

3. CHI-CHI EARTHQUAKE, TAIWAN

On September 21, 1999, at 1:47am (local time), the Chi-Chi earthquake struck the central area of Taiwan. This earthquake, measured at a moment magnitude of 7.6, caused more than 2,400 death and over 10,000 injuries according to the Taiwanese Official Report. Approximately 10,000 buildings and homes collapsed and about 7,000 more were severely damaged.

Highway bridges including those constructed under modern seismic design codes were severely damaged as well. Based on the Taiwanese Highway Bureau's preliminary report (Yeh, Nov., 1999), at least nine bridges were severely damaged including three which were under construction. Five bridges collapsed due to fault rupture at the site and seven more structures were moderately damaged. Through the joint efforts of the Federal Highway Administration (FHWA), Ministry of Transportation and Communication (MOTC) of Taiwan, an investigation team was formed to examine and collect information on highway bridge performance. The team members consisted of FHWA and Taiwanese Highway Bureau (THB) personnel and the National Expressway Engineering Bureau's (NEEB) Engineers of MOTC. During the investigation, the team visited 10 bridge sites which included 2 sites belonging to the NEEB and 8 sites belonging to the THB. Figure 2 shows the epicenter and associated faults of the Chi-Chi earthquake. Taiwan is located at the junction of the Manila and Ryukyu Trench in the Western Philippine Sea where the Philippine Plate is being forced under the Eurasia Plate. The Philippine Plate is moving in a northwest direction which causes a significant strike-slip component along the northern portion of the Manila Trench and essentially creates a "transpressional" effect (plate was pushed up due to transverse compressions from both sides) which has lifted the island of Taiwan microplate up relative to its larger tectonic neighbors. This "thrust fault" or so-called reverse-slip fault had elevated several locations including bridge sites by as much as 30 feet.

Observed Damage:

1- Bearing failure and superstructure offset, both horizontally and longitudinally

2- Collapsed or tilted bridge piers due to shear or ground failure

3- Bridge spans sliding off the seat and collapsing because of large ground movements

4- Connection failures between bridge bearings and pier caps, resulting shear cracks in the PS/C beams

5- Cable failure in a cable-stayed bridge

6- Abutment back-wall failure

7- Foundation failure caused by fault rupture or by soil liquefaction

4. BRIDGE LESSONS LEARNED

After extensive visits and evaluations of both damaged and undamaged bridge sites, the following are the preliminary findings and lessons learned from these three post-earthquake investigations:

- *Shear key and bearing design needs to be consistent with pier design capacity.*

In the Kocaeli earthquake, shear key failures due to lack of proper detailing and construction allowed a large offset on the Sakarya Viaduct of the TEM (see Figure 3). If the shear keys were able to provide adequate lateral resistance, much of the associated damage might have been avoided. However, the shear keys should not be designed stronger than the bridge pier to avoid incurring damage in the bridge foundations or piers, since foundation damage is more difficult to repair.

- *The shear capacity of connection details needs to be consistent with the design of other components.* The majority of the energy absorbing "C-elements" of the EDUs used in Viaduct #1 did not absorb much energy during the Duzce earthquake, since the shear failure of the connecting bolts to the pier prevented the EDUs from functioning properly. Thus, balanced design between all components is needed to prevent malfunction of the whole system (Figure 4 shows the premature EDU failure)

- *Global system effects need to be compatible with local members.* The severe damage to the superstructure of Viaduct #1 might have been avoided if the hybrid system of EDUs, pot bearings and sliders interface were designed for the same displacement capacity. The pot bearing's failure due to insufficient displacement capacity prevented the EDUs from functioning properly. This disabling of the global system by a local failure is a reminder that "the devil is in the details". It also underscores the need to consider displacement capacities of critical members as well as forces in seismic design.

- *Generous seat width to accommodate unexpectedly large movements caused by ground failure or strong tremors is a very sound investment.* Bridges with irregular geometry, such as those with skewed or curved alignment, are more vulnerable to loss of support failure, and to bearing damage due to rotational moment. Extra seat width will prevent unseating of the superstructure in many cases. However, fault rupture, directly crossing or immediately adjacent to the bridge, is a catastrophic event and span collapse is inevitable if the displacements are large. (Figure 5 shows the Shi-wei Bridge that collapsed due to superstructure unseating. The surface fault rupture crosses their piers.

- *Long-span bridges, especially those still under construction, are vulnerable to near-fault effects.* The Ji-lu Bridge, located near Chi-Chi town, is a cable-stayed bridge. The structure was almost complete at the time of the earthquake; only one section under the tower and the guardrail were not completed. Damage to the bridge includes a cable fracture, cracking and spalling in the concrete tower, pot bearings failure due to structure pounding and approach spans offset in the transverse direction. Ground motion, with a high pulse in the longer natural period, recorded in the near station have also indicated that bridges with a longer natural period might be vulnerable to strong ground motion. Figure 6 shows the Ji-lu Bridge with almost complete superstructure by missing one section adjacent to the pylon.

- *Ground failures may cause structural failure.* The ground failure of the Bei-feng bridge is located near the Shi-kan Dam (lifted up about 10 m). This bridge's spans collapsed due to a fault rupture underneath the bridge. The rupture lifted the upper stream by 5-6m, and created a new waterfall. This reverse-slip fault also shortened the bridge length and may have pushed the second pier to fail. Please Figure 7.
- Bridge pier shear failures should be prevented. Figure 8 shows the South-Bound bridge piers of the U-Shi bridge had severe shear cracks and failed. Shear reinforcement design needs to be considered in resistance of all directions. If the shear failures of this bridge were prevented through proper design, damage to the newer bridge would have been very limited.

- *Cantilever overhang connections are vulnerable to shear failure, particularly for curved or skewed bridges*. Figure 9 shows shear cracks of a horizontal curved viaduct with a steel superstructure supported on the single concrete column piers. Some of these are "C – shaped with steel pier-caps cantilevered off the column resulting in an eccentric connection to the column. Although the bridge did not collapse, it had serious shear cracks. Most of the eccentric connections showed distress in the concrete columns. Those shear cracks could have contributed through the vertical acceleration component for this cantilever overhang superstructures by amplifying the dead loads (see Figure 9).

- *Near faults ground motion was intense and its effects need to be studied in combination with the vertical acceleration component.* This was shown by the detailed inspection of the Tong-tou bridge, which was near the epicenter of the Chi-Chi earthquake. The first and fourth spans collapsed. The second span tilted and rotated horizontally in transverse direction. There was severe substructure failure because the pier column bents sheared out completely. Large movements due to the fault rupture underneath the bridge contributed to this failure. It is very unusual to have a right-bridge collapse because its superstructure rotated completely off its supports.. Figure 10 shows the collapsed spans of the bridge.

5. SUMMARY and CONCLUING REMARKS

Design codes that were used in Taiwan and Turkey are similar to the AASHTO Bridge Design Specifications, especially for the newer bridges. Through extensive inspection and studies of damaged and undamaged bridges following these three earthquakes, lessons learned were valuable for improving the seismic design of bridges. Near fault effects and vertical acceleration need further study to properly understand the failure of bridges adjacent to faults.

The three earthquakes severe resulted in damage to highway bridges because of the large ground motion and fault ruptures directly beneath or adjacent to bridge sites. Even with use of modern design codes, bridges can not be expected to resist such large displacements or offsets in either the superstructure or by the substructure. The challenge facing engineers now is to develop a strategy to deal with a bridge constructed across or near-by a known fault.

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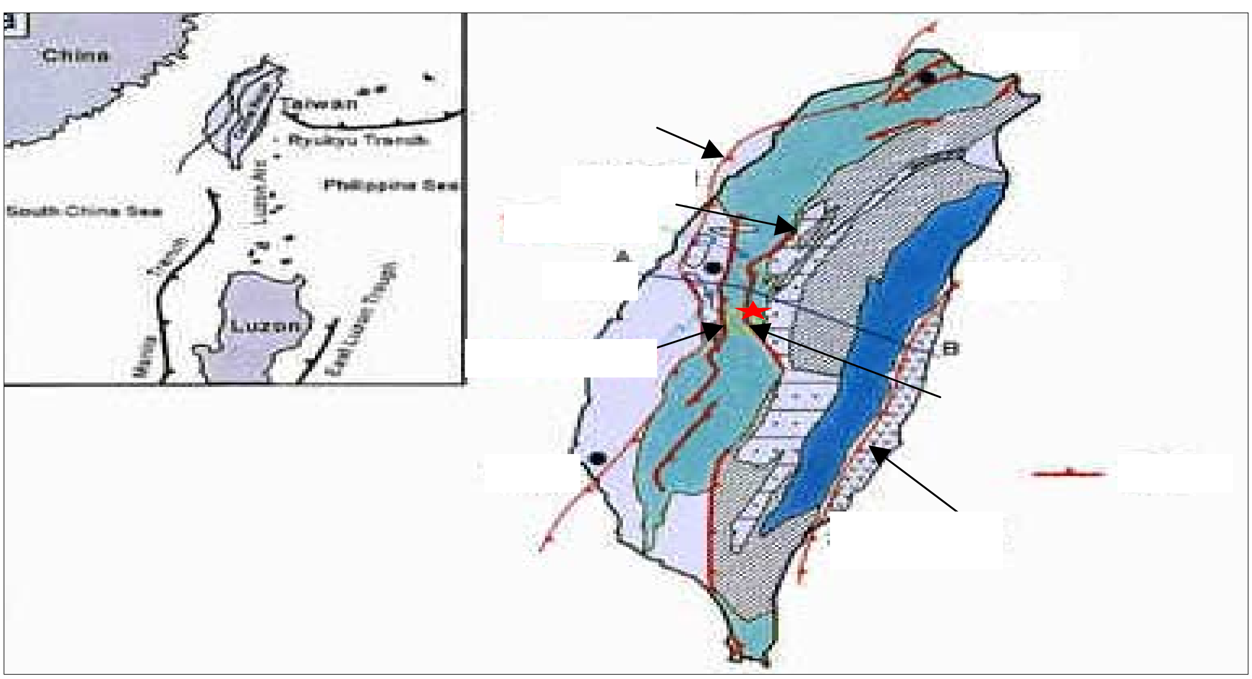

Figure 2. Map showing the location of Chi-Chi earthquake and associated Faults in Taiwan

Figure 3. Shear keys failure in Sakarya Viaduct

Figure 4. EDU failure

Figure 5. Spans collapsed of Shi-wei Bridge

Figure 6. Cable fracture of a cable-stayed

Figure 7. Spans Collapsed due to Fault Rupture

Figure 8. Pier shear failure of U-Shi Bridge

Figure 9. Shear racks on eccentric connections

Figure 10 Spans collapsed of Tong-tou Bridge