Bolu Viaduct: Damage Assessment and Retrofit Strategy

by

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ABSTRACT

In 1999, two major earthquakes struck Turkey, resulting in more than 15,000 fatalities and over 30,000 injuries. The first earthquake, called the Kocaeli earthquake, was caused by a right lateral strike-slip type rupture along the main strand of the North Anatolian Fault (NAF). It occurred on August 17 and had a moment magnitude (Mw) of 7.4. The second earthquake, the Duzce earthquake, with a moment magnitude of 7.2, occurred on November 12 along the secondary Duzce fault, a branch of the NAF. According to seismologists, the rupture on November 12 resulted from the stress created by the Kocaeli earthquake. The epicenter of Duzce earthquake occurred very close to the Bolu Viaduct, a 2.3 km long elevated highway structure located on the last segment of Trans-European Motorway (TEM) which was under construction. The Bolu Viaduct, which utilized a hybrid isolation system, suffered extensive damage due to propagation of a surface fault rupture between segments of viaduct piers. This paper describes the design challenges encountered during the development of the retrofitting strategy for the Bolu Viaduct and the final retrofit scheme utilizing Friction Pendulum Isolation Bearings.

KEYWORDS: seismic design, retrofit, fault rupture, isolation bearings

1.0 INTRODUCTION

The November 12, 1999 Duzce earthquake with a moment magnitude of 7.2, was caused by a right lateral strike-slip rupture along the secondary Düzce fault near the town of Düzce *(Figure 1)*. This fault is connected to the main segment of the North Anatolian Fault (NAF) by the Elmalik and Asagi Bakacak faults. The length of the surface fault rupture is estimated to be 40 km with an average lateral offset of 4m along most of its length. Figure 1 depicts the epicenters of both Kocaeli and Duzce Earthquakes.

At the Duzce station near the epicenter, a 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. The Bolu Viaduct is located between these two stations, in the town of Kaynasli. The Duzce earthquake caused considerable damage to the superstructure of the Bolu Viaduct due to the close proximity of the fault rupture.

The repair and retrofit construction program for Bolu Viaduct is already underway to upgrade its seismic capacity so as to withstand future earthquakes stronger than the Kocaeli and Duzce Earthquakes.

2.0 BOLU VIADUCT

The Bolu Viaduct, with its 59 spans and dual 2.3 km structures, was approximately 95% complete and awaiting installation of expansion joints to complete the project at the time of the earthquake (*Figure 2*). Its 40 m spans are comprised of 7 lines of simply-supported, prestressed concrete box girders (V-girders) seated on pot bearings with stainless steel PTFE-slider interface. The V-girder is a precast, open-box beam with narrow bottom flanges, moderately battered webs, and small top flanges. The cast-in-place (CIP) deck slab is continuous

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over 10 spans. The piers are single, CIP, octagonal hollow-core reinforced concrete columns, 4.5x8.0 meters in plan dimension with heights varying from 10 m to about 49 m. They were designed and detailed to provide ductile behavior during earthquakes. The piers are founded on massive reinforced concrete footings, supported in turn on twelve 1.8m diameter cast-in-drilled-hole. The piles pass through surficial soils of variable strength and bear on alluvial layers, generally at a depth of 30m.

The Viaduct had also incorporated an Energy Dissipation Unit (EDU) system, which is installed on each pier cap to accommodate longitudinal thermal movements and to reduce seismic forces through energy dissipation during a major event. The EDU's consisted of C-shaped energy dissipating steel elements, which are referred to as crescent moons (*Figure 3*). These elements provide hysteretic behavior through yielding of the steel elements. In addition to the crescent moons, a piston and a sliding unit were incorporated into the EDU's at the expansion joints and at the center pier of each 10-span continuous segment. Therefore, seismic resistance relied primarily on the EDU systems and pot bearings. Shear blocks adjacent to beams 3 and 5 restrained transverse displacements as a secondary line of defense in the event of extreme displacements. Longitudinal movements at expansion joints were constrained by cable restrainers to prevent the end girders from falling off their supports (*Figure 4*).

In summary, during normal environmental conditions (i.e., thermal expansion) the viaduct movements are accommodated by the PTFE-slider interface of the bearings in conjunction with the sliding unit of the EDU’s, which is controlled by the piston incorporated into the units. However, during the design level earthquake, the pistons would lock up similarly to a shock absorber and engage all of the EDU's on each 10-span continuous deck segment. This was intended to dissipate the energy induced by the ground motion, and reduce the displacement response and the total force exerted on the substructure.

3.0 POST-EARTHQUAKE DAMAGE ASSESSMENT OF BOLU VIADUCT

The Bolu Viaduct was subjected to extensive damage and narrowly escaped collapse during the Duzce earthquake. A surface fault rupture crossed a segment of the Viaduct between piers 45 and 47 (*Figure 5*). Evidence of high velocity impulses was observed from the earthquake records and from on-site inspections.

There are indications that such impulses present special problems for bridges and tall buildings. These problems are manifested by very large displacements, overturning moments, and other energy sensitive structural responses.

Significant damage did occur to all the EDUs and bearings of Bolu Viaduct, from surface rupture displacements and ground shaking (*Figure 6)*. These caused the girders to translate on top of the piers about 1100 mm longitudinally and 500 mm transversely. Observation of the scratch signs on the surface of the stainless steel plates indicates that the bearings slid off their pedestals probably in a very early stage before any significant cyclic movement.

Impact between the ends of the central beam and the concrete pedestal supporting the EDUs occurred at most spans, destroying many of the support pedestals and damaging many of the beam-ends. Impact between the transverse shear keys and the sides of the girders caused extensive damage to the shear keys, and some damage to the girders. The hollow reinforced concrete pier stems were largely undamaged, though a number of piers have small but significant tilting and rotation. At the location of the fault rupture crossing, piers rotated about their vertical axis by 3.6 degrees. Also, limited damage to the foundation system was observed at vicinity of fault crossing where plastic hinging at top of the piles and significant pile-cap cracks were noted.

The Bolu Viaduct was designed for a 500-year return period based on the 1992 AASHTO Standard Specifications for Highway Bridges and the Euro Code for seismic isolation design.

However, it appears that, due to the close proximity of the fault rupture, the viaduct experienced a PGA in excess of its 0.54g design value.

4.0 REPAIR/RETROFIT DESIGN STRATEGY

As part of the retrofit it was necessary to replace both the damaged sliding pot-bearings and the damaged EDUs. Seismic isolation of the superstructure from the piers was identified early on as essential for the repair/retrofit of the elevated highway. Also, the use of seismic isolation technology assured that the piers of the Bolu Viaduct will remain elastic for future major earthquakes. As part of the retrofit design program, the original (1992) probabilistic seismic hazard studies for ground shaking and fault rupture were updated to include more recent data, particularly the two 1999 earthquakes. The Italian consultants (G.M. Calvi and Nigel Priestley) carried out the design of the repair and retrofit of the damaged elevated highway.

In consideration of all seismological studies, it was agreed with the Client (Turkish Government Karayollari Genel Mudurlugu) that the input ground motion should be characterized by the following properties:

- Design peak ground acceleration (PGA) 0.81g, which corresponds to a 2000-yr return period
- Design peak spectral acceleration (PSA) 1.8 – 2.0g at %5 damping
- Design peak spectral displacement (PSD) 600mm, resulting from a future fault rupture at the site
- Consideration of possible near-field effects

In addition to the demand arising from the ground motion, a permanent ground deformation resulting from ground creep and fault slip equal to +/- 250mm was considered during the design life of the viaduct.

Based on the previous studies and these assumptions, a set of fifteen horizontal and two vertical accelerograms was developed and used for all non-linear analyses. The set of accelerograms was selected to satisfy as much as possible the following additional conditions, which characterized the Duzce fault and the location of the Bolu Viaduct itself:

- The Richter-scale magnitude of the earthquake should be of the order of 7-7.2, consistent with the characteristic earthquake on the Duzce fault (Lettis et al., 2000).
- The earthquake fault rupture should be strike-slip.
- The bridge site should be located with respect to the epicenter in such a way that the angle between the fault and the line connecting the epicenter and the bridge is clockwise and small.
- Peak ground acceleration for the repair was taken to be 0.81g, which corresponds to a return period of 2000yr.
- The “near-field effect” to be considered per AASHTO Edition 2000 (all the records are from near-field locations and have been produced by source mechanisms reasonably similar to the strike-slip events typical of the Bolu area).
- The Design Criteria utilize a fully isolated bridge with isolation bearings at all piers and abutments. The isolation bearing design fully complies with the 1999 AAHTO Guidelines for Seismic Isolation Design.

5.0 EMERGENCY SUPPORT MEASURES

Soon after the Duzce earthquake, temporary steel trusses on both sides of the pier cap were added to three piers to support the unseated span ends and to prevent collapse in the event of moderate aftershocks (*Figure 7*). The 130 ton steel trusses were raised into position using deck-mounted lifting and clamped to the pier caps by prestressing tendons. In addition, cable restrainers were installed at the abutments to prevent excessive movement of the end spans.

Since the 1999 Earthquake the local seismicity has been reassessed, resulting in a significant increase in the design level of ground shaking intensity (PGA=0.81g), as compared to the original design level (PGA=0.54g). As a consequence, the repair and retrofit strategy requires more than just repositioning of the Bolu Viaduct to its original condition, which is briefly summarized as follow:

6.0 THE VIADUCT REPOSITIONING

The repositioning of the viaduct will be undertaken for an entire 10-span segment at a time. But first the EDU support blocks, transverse shear restraint blocks and broken EDUs will need to be removed before repositioning occurs. Next, the displaced span ends are to be lifted and placed on temporary supports and low-friction sliders (3 to 5 percent). Then, the longitudinal repositioning will take place by using two hydraulic jacks positioned at each of three piers of the 10-span segment, using the piers as reaction points. It is important to note that exact repositioning is not possible because of small permanent deformations at pier caps relative to the ground. Once the longitudinal repositioning is placed, a similar procedure is used to move the 10-span segment to its final position transversely. Figure 8 shows the jacking system used for viaduct repositioning.

7.0 SUPERSTRUCTURE RETROFIT

A decision was made to make the 10-span segments fully continuous for live load and differential thermal movements. This will involve casting a new full-depth transverse prestressed concrete diaphragm at each internal support by closing the ends of the beams and by confining the end 600mm of the girders of the two adjacent spans (*Figure 9*). This approach will avoid the unseating of the beams during major earthquakes. At the expansion joints, two separate prestressed diaphragms will be cast at each end span. Two isolation bearings would be utilized at the internal support between the diaphragm and the pier cap and four isolation bearings at the expansion joints.

8.0 PIER RETROFIT

Overall, the hollow reinforced concrete piers performed well and only minor flexural cracking was observed on some piers. However, piers 45 and 47, the closest to the fault rupture crossing, experienced small rotations and a number of other piers experienced minor tilting. In the final dynamic analysis, the seismic isolation approach eliminated the need for any retrofit measures for the pier stems.

9.0 FOUNDATION RETROFIT

For the few footings where significant damage occurred due to crossing of fault rupture or the tilting and rotating of the pier stems, retrofit measures were proposed. Such measures included additional piles and footing extensions.

10.0 FRICTION PENDULUM ISOLATION BEARINGS

The client commissioned a study by High-Point Rendel of London, to undertake an industry survey of seismic isolation systems to identify the isolation system most suitable for the demanding environmental and high seismic performance requirements of the project. The high performance requirements included reliable dissipation of the large amounts of energy caused by the near field effects, and accommodation of a large permanent fault rupture offset without damaging the isolation unit and the viaduct. On the basis of this study, Friction Pendulum bearings were selected for the retrofit of the Bolu Viaduct (*Figure 10*).

Figure 11 illustrates the basic principles of the Friction Pendulum bearing. The bearing uses the characteristics of a pendulum to lengthen the natural period of the isolated structure so as to avoid the strongest earthquake forces. It uses pendulum motion and friction to dissipate the energy of an earthquake forces. Earthquake-induced differential displacements occur primarily in the bearings, and lateral loads and shaking movements transmitted to the substructure are greatly reduced. The period of the bearing is determined by the radius of curvature of the concave surface. It is independent of the mass of the supported structure.

In the final design approach, two isolation bearings will be utilized at the internal support between the diaphragm and the pier cap and four isolation bearings at the expansion joints. In order to optimize the design and to consider the variation in the height of the piers and the crossing of the fault rupture at a specific location, three different Friction Pendulum isolation bearings are to be used. These are;

- Displacement capacity +/- 700mm, large radius (smaller height piers and abutments)
- Displacement capacity +/- 700mm, small radius (tall piers)
- Displacement capacity +/- 900mm, large radius (piers P40 to P50, where the fault rupture crossed during Duzce earthquake)

11. CONCLUSIONS

The response of the Bolu Viaduct to a fault rupture during the 1999 Duzce Earthquake highlights the importance of designing for permanent ground movement and providing a restoring force capability in the design of a seismic isolation system, especially for structures located near an active fault. The existing seismic design codes for highway bridges, including the1999 AASHTO Guide Specifications for Seismic Isolation Design, do not address the subject of accommodating permanent fault displacement. Near fault effects need further study to properly understand the failure of bridges constructed across or adjacent to a known fault. Lessons learned from the Duzce earthquake and similar earthquakes in recent years are valuable for improving the seismic design of highway bridges located near known faults.

12. ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at the Turkish KGM, Earthquake Protective Systems Incorporated, and High-Point Rendel for their cooperation and assistance during the investigation of Duzce earthquake.

13. REFERENCES

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Figure 1- Map showing the North Anatolian Fault Zone

Figure 2- General view of the Bolu Viaduct

Figure 3- A Pot bearing and an EDU unit

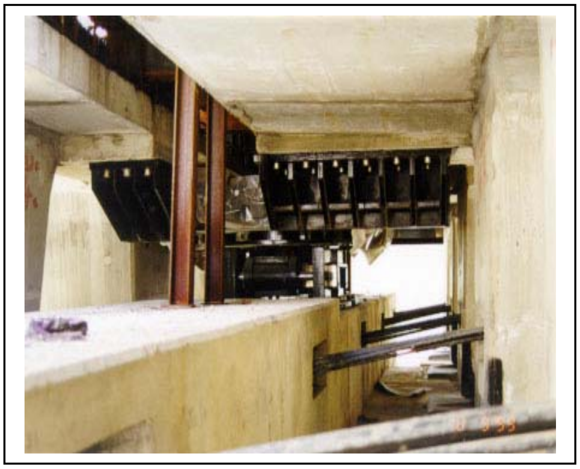
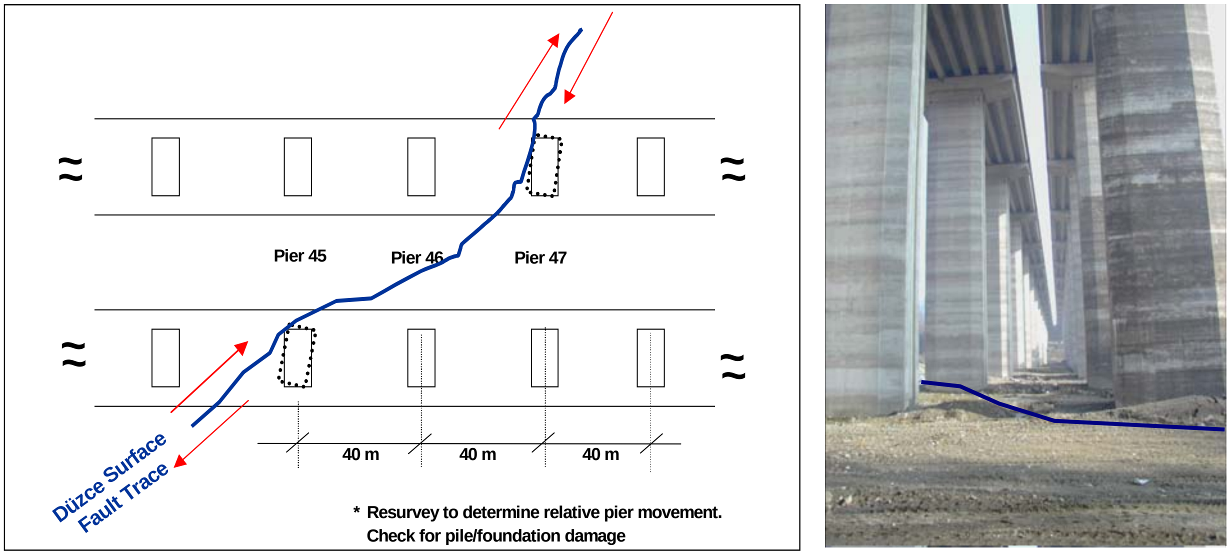


Figure 4- Cable restrainers at the expansion joint



*** Resurvey to determine relative pier movement. Check for pile/foundation damage**

Figure 5- Fault trace between piers 45 and 47

Figure 6- Damage to an EDU, shear key and a pot bearing

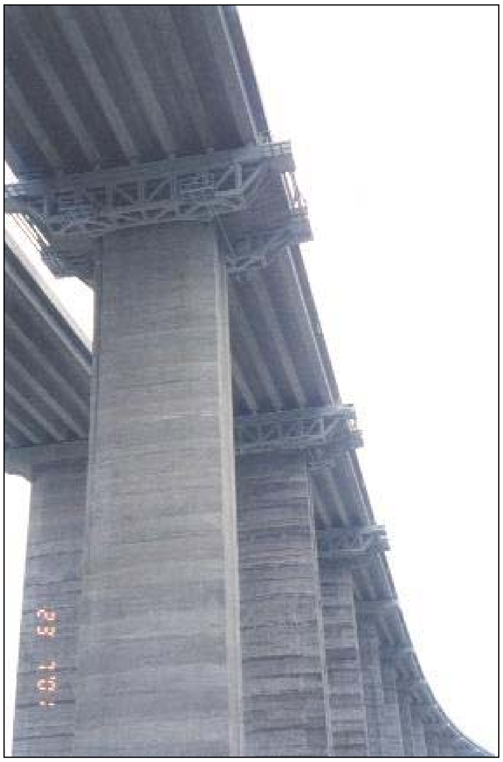


Figure 7- Temporary truss supports

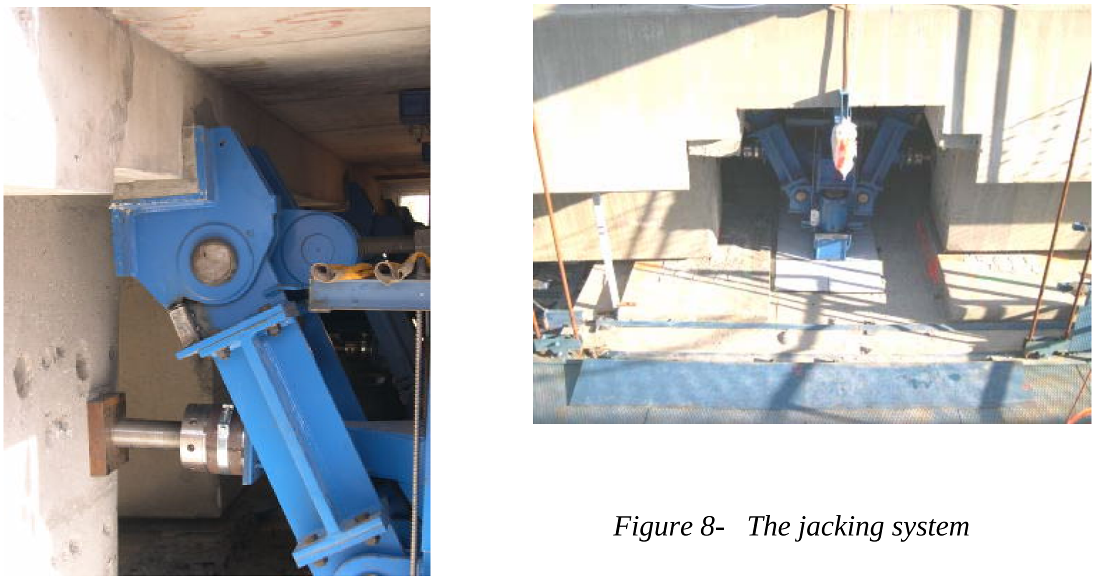


Figure 8- The jacking system

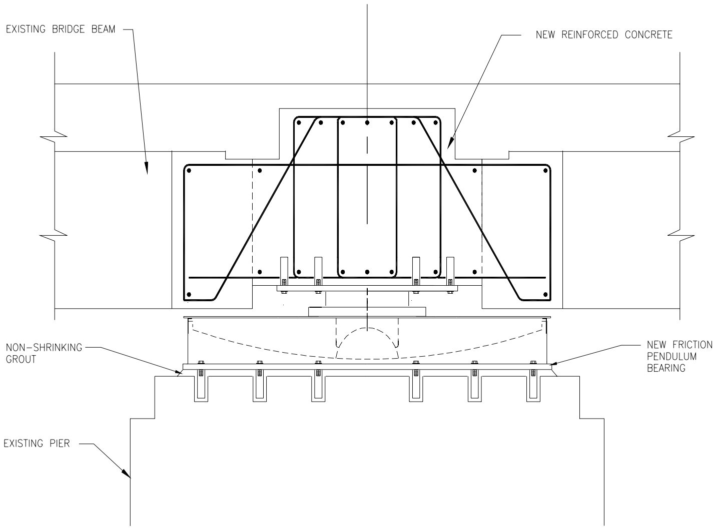


Figure 9- Retrofit scheme at typical interior pier

Figure 10- Friction Pendulum Isolation bearing

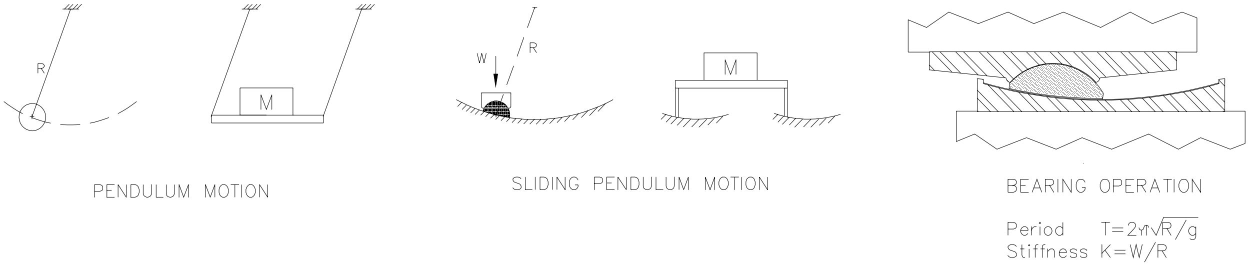


Figure 11- Basic Principles of Friction Pendulum bearings