Title

Evaluation of collapse and non-collapse of parallel bridges affected by liquefaction and lateral spreading.

Permalink

https://escholarship.org/uc/item/1nh3q8mw

Authors

Turner, Benjamin
Brandenberg, Scott J
Stewart, Jonathan P

Publication Date

2013-03-01

10CUEE CONFERENCE PROCEEDINGS
10th International Conference on Urban Earthquake Engineering
March 1-2, 2013, Tokyo Institute of Technology, Tokyo, Japan

EVALUATION OF COLLAPSE AND NON-COLLAPSE OF PARALLEL BRIDGES AFFECTED BY LIQUEFACTION AND LATERAL SPREADING

Benjamin Turner 1), **Scott Brandenberg** 2), **and Jonathan Stewart** 3)

1) Graduate Student Researcher, Department of Civil and Environmental Engineering, University of California, Los Angeles.
2) Associate Professor and Vice Chair, Department of Civil and Environmental Engineering, University of California, Los Angeles.
3) Professor and Chair Department of Civil and Environmental Engineering, University of California, Los Angeles.
bjturner@ucla.edu, sjbrandenberg@ucla.edu, jstewart@seas.ucla.edu

Abstract: An overview is presented of the authors' ongoing investigation of the performance of a railroad bridge and adjacent highway bridge during the 2010 El Mayor-Cucapah earthquake in Baja California, Mexico. A span of the pile-supported railroad bridge collapsed due to movement of a pier from lateral spreading. The highway bridge, supported on drilled shafts, suffered moderate structural damage but did not collapse. An overview of the site, structural details of the bridges, and the proposed geotechnical explorations and analyses are presented. The Pacific Earthquake Engineering Research Center (PEER) recently published "Recommended Design Practice for Pile Foundations in Laterally Spreading Ground," which synthesizes the last decade of research on the topic. Using the results from planned geotechnical investigation, the authors intend to analyze the bridges according to the PEER guidelines. The case studies will provide valuable insight for validating the recommended guidelines.

1. INTRODUCTION

On April 4, 2010, the M_w 7.2 El Mayor-Cucapah earthquake occurred southwest of Mexicali in northern Baja California, Mexico (USGS 2010). Liquefaction-related damage to irrigation and transportation infrastructure, buildings, and agricultural land was widespread throughout the region (GEER 2010). This paper focuses on an ongoing study of two parallel bridges located about 60km southeast of Mexicali that were subjected to liquefaction-induced lateral spreading and vertical settlement during the El Mayor-Cucapah earthquake.

Although the two bridges were subjected to the same level of lateral spreading demand, their performance levels were different, making this a valuable case study. An overview of the observed damage and structural details of the bridge along with the authors' planned site investigations and analyses are presented in the following sections. The primary focus of the investigation and analyses will be to model the highway bridge in an effort to understand why it exhibited desirable performance while the railroad bridge collapsed.

2. REGIONAL GEOLOGY AND SEISMICITY

The Mexicali Valley and its counterpart on the USA side of the border, the Imperial Valley, are located in the Salton Trough, an extensional basin formed by tectonic activity along the transform boundary between the Pacific and North American plates (Figure 1). To the southeast, the Gulf of California represents further extension due to divergent fault step-over at the plate margin, while movement to the northwest is primarily strike-slip along the San Andreas Fault system. The Colorado River enters the east side of the basin near the Mexico-USA border, depositing alluvium over marine deposits for a total soil thickness up to 2,400m thick (GEER 2010). High groundwater levels from the river and agricultural activity combined with the loose alluvial deposits create a high liquefaction hazard throughout the valleys.

Several faults cross the region, primarily accommodating strike-slip movement in the northwest-southeast direction and extension in the northeast-southwest direction. The El Mayor-Cucapah earthquake occurred mainly along the Pescadores and Borrego faults northwest of the epicenter and the previously unknown Indiviso Fault to the southeast, which was buried beneath sediments of the Colorado River delta prior to the earthquake. The offset was oblique with the primary component being strike-slip (GEER 2010).

The northern Baja California region is known to be seismically active, with several major earthquakes occurring in recent history. The El Mayor-Cucapah earthquake was the largest recorded event in the region since an estimated Mw 7.2 event in 1892 (Hough and Elliot 2004).

3. SITE DESCRIPTION

Immediately following the earthquake, a team of researchers from the Geotechnical Extreme Events Reconnaissance (GEER) Association visited the Mexicali and Imperial Valleys to collect perishable geotechnical data

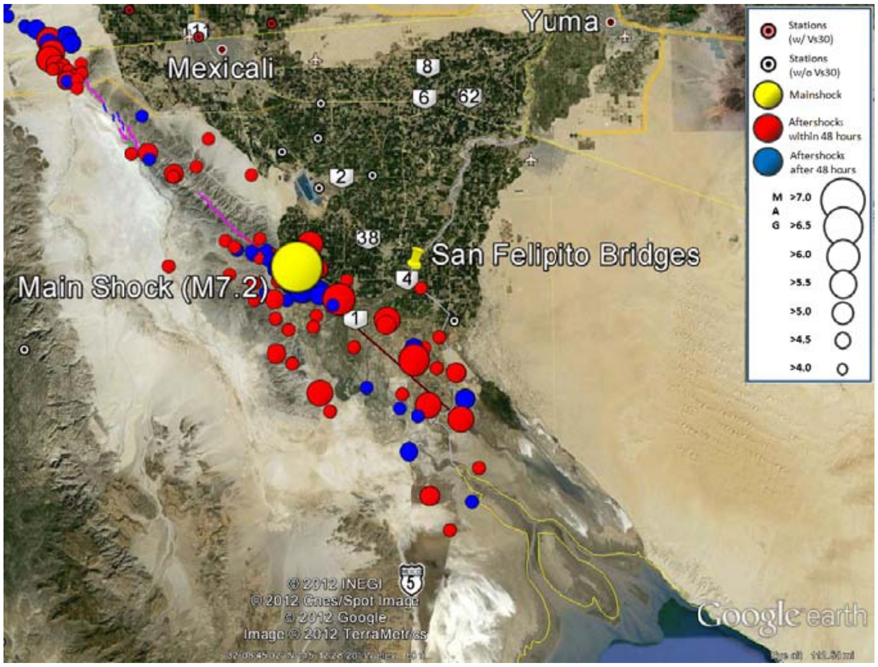

Figure 1: Regional map showing main event, aftershocks, and site location. After GEER Report (2010).

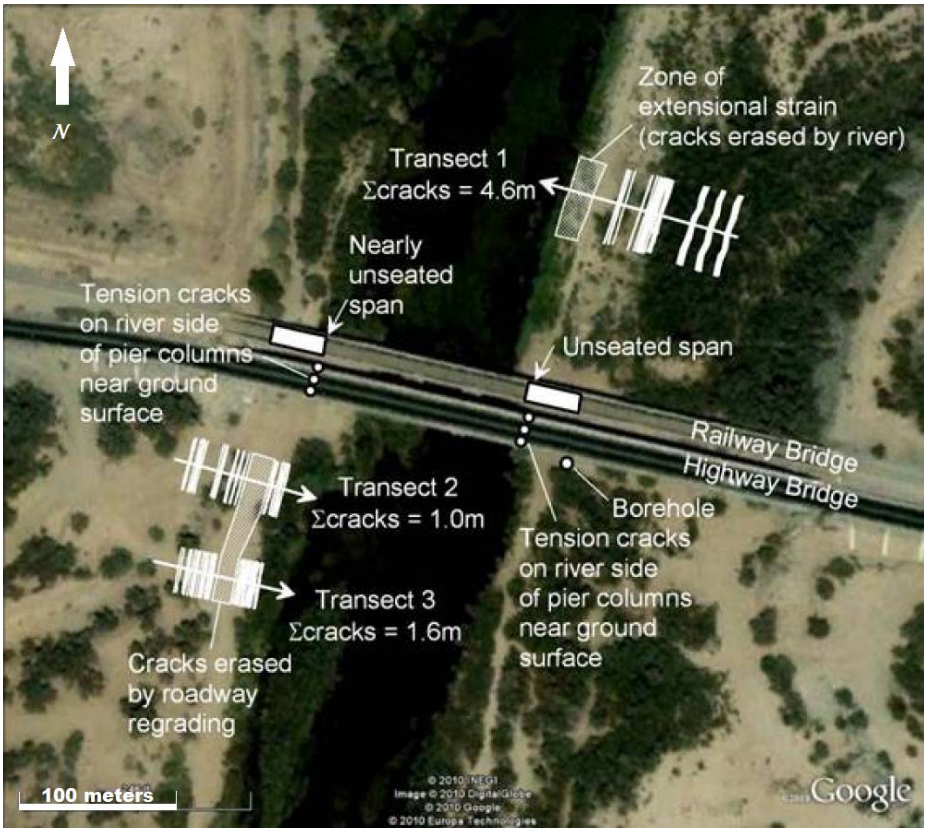

Figure 2: Site map showing lateral spreading and observed structural damage to bridges. After GEER Report (2010).

and observe structural damage associated with geotechnical issues. Except as noted, the following information in Sections 3 and 4 is adapted from the report of their reconnaissance effort, available on the GEER website (GEER 2010).

Two closely-spaced, parallel bridges span the Colorado

River at the site, a railroad bridge and a highway bridge, collectively called the “San Felipito Bridges” (see Figure 2). The river is flanked on both sides by relatively flat agricultural land with gently sloping banks. The nearest ground motion station to the site, located in Riito approximately 12km to the southeast, recorded a peak ground acceleration of approximately 0.4g.

3.1 Geotechnical Conditions

The near-surface soil profile at the site generally consists of recent alluvial deposits of loose sand with varying amounts of silt. The Secretaría de Comunicaciones y Transportes (Secretariat of Communications and Transportation) de México (SCT), the government agency with jurisdiction over the highway bridge, conducted a soil boring during the GEER reconnaissance trip. The soil profile inferred from their boring log consist of 6m of silt overlying approximately 5.5m of loose sand, underlain by dense sand, with the groundwater table at a depth of 2m. The location of the boring is shown in Figure 2. Further site investigations including subsurface testing are planned as described in Section 5.0.

3.2 Ground Failures

As shown in Figure 2, lateral spreading cracks were observed on the river banks both north and south of the bridges in the non-liquefied silt crust that overlays the liquefiable sand. It was not evident from the initial reconnaissance whether or not the approximately 4m of silt below the groundwater table liquefied during the earthquake. The sum of the measured lateral spreading cracks was as much as 4.6m along a transect about 60m north of the bridge, although not all the deformation could be directly measured due to heavy vegetation cover and erosion of cracks by the river prior to the arrival of the GEER team.

Measured lateral spreading deformation was greater on the east bank of the river than the west bank, possibly because the river currently flows along the western margin of its floodplain so the alluvial sediments on the east bank are younger and hence looser and more susceptible to liquefaction. This observation could have implications for estimates of potential lateral spreading deformations at similar sites.

Vertical settlement of up to 0.5m was observed, likely due to a combination of reconsolidation following liquefaction and deviatoric deformation. At the location of the largest measured vertical ground settlement, the bridge pier settled approximately 0.5m, likely due to static loads, down-drag forces mobilized during liquefaction, and a loss of axial resistance.

4. BRIDGE DAMAGE AND STRUCTURAL DETAILS

Both bridges have precast-prestressed concrete simply-supported spans on elastomeric bearings resting atop reinforced concrete, pile-supported piers. Although both bridges were founded on deep foundations, the railroad bridge suffered unseating collapse of one span and near collapse of two other spans, while the highway bridge suffered only moderate structural damage without collapsing. Further structural details of the bridges are provided in the following two sections.

4.1 Railroad Bridge

Constructed in 1962, the railroad bridge consists of a single track supported on three approximately 1.0m-deep T-shaped girders. The simply-supported spans rest on elastomeric bearings atop reinforced concrete pier walls which are supported on driven pile foundations. No other positive structural connection between the girders and the pier walls was observed, e.g. shear keys and diaphragm anchorage as described below for the highway bridge. The research team has not obtained construction plans for the railroad bridge at this time, although we anticipate receiving these drawings through coordination with Mexican colleagues.

Damage to the railroad bridge consisted of collapse of a span on the eastern side of the river as lateral spreading translated and rotated the pier at the western end of the span towards the river, exceeding the lateral capacity of the elastomeric bearing and leading to unseating of the girders. The superstructure also displaced in the transverse direction relative to the pier. Similar movement of piers on the west bank of the river nearly led to collapse of two additional spans. Temporary steel trestles were erected to replace the collapsed span and support the nearly-collapsed spans.

4.2 Highway Bridge

The following structural details are based on the bridge construction plans (1998) provided to the research team by SCT.

The highway bridge consists of approach fills up to 6m thick leading to ten 20m-long simply-supported spans (Figure 3). Each span consists of seven precast-prestressed 1.15m-deep I-shaped girders spaced approximately 1.6m on-center in the transverse direction. Precast slab panels rest on the top flanges of adjacent girders, covered by a cast-in-place deck slab. The deck slabs are cast continuously across spans 1-2-3, 4-5-6-7, and 8-9-10, i.e. in three separate sections. The girders are supported on 60cm-wide concrete masonry plates on 1.6m-wide pier caps, which are in turn supported on four extended shaft columns. The elastomeric bearings are 20cm wide in the longitudinal direction.

Vertical diaphragms connect the ends of the girders in the transverse direction. A prestressing strand in the transverse direction passes through the diaphragms and ducts in the girder-ends across the entire 11m width of the bridge, forming a continuous member to provide lateral force resistance in the transverse direction.

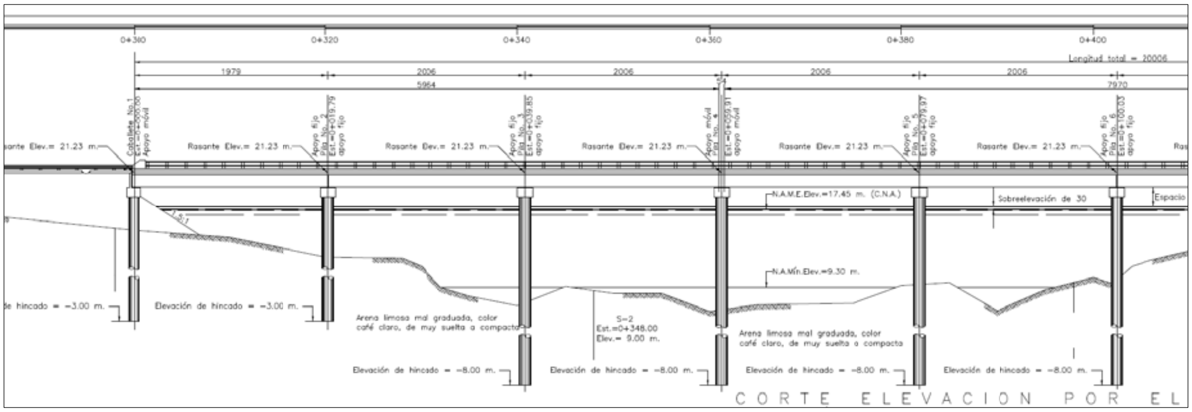

Figure 3: Western half of highway bridge, from original construction plans (SCT 1998).


(a)

(b)

(c)

Figure 4: (a) shear key damage at pier cap (photo Richard Woods), (b) vertical ground settlement relative to columns (photo Jim Gingery), and (c) column flexural concrete cracking at base (photo Richard Woods).

The girder-to-pier-cap connections are a mix of "pinned" and "roller bearing" types. At the piers between spans 3-4 and 7-8, as well as at the end supports at the abutments, the only connection between the girders/diaphragm and the pier cap is the laminated neoprene elastomeric bearing. The bearing transfers axial load and allows for rotation and translation of the girders by compressing and deforming in shear, respectively. A polymer-filled expansion joint is constructed in the deck slab at these locations to allow for thermal expansion and contraction.

At the remaining piers, the deck slab is continuous over the joint and translation of the girders is restrained by anchorage via two rectangular blocks that extend from the base of the diaphragm into the pier cap. The anchorage blocks fit into a rectangular slot cast into the pier cap such that translation is restrained in both the longitudinal and transverse directions. There is no positive connection between the diaphragm anchorage blocks and the pier cap via reinforcing bars that are continuous across the joint; an asphaltic felt pad is placed between the two elements. A small amount of rotation is allowed at these “pinned” type connections. The end conditions of all ten spans are considered simply-supported.

The four 1.2m diameter extended shaft columns are continuous with four drilled shaft foundations of the same diameter at each pier. There are no pile caps, although the shafts are connected with a transverse beam near the ground level for the shafts in the river, likely to prevent erosion (visible in Figure 4c). The 1.5m high abutment walls are supported on three 1.2m diameter drilled shafts. The foundations in the river extend to the deepest elevation, approximately 14m below the pile cap, while the foundations nearest the abutments and beneath the eastern spans where flow is seasonal are shorter by 3m to 6m. Assuming horizontal stratigraphy at the site, the deepest foundations extend about 10m into the dense sand layer.

Three separate zones of damage were observed on the highway bridge, shown in Figure 4 (GEER 2010; Meneses et al. 2010):

1. 30-cm-tall shear key “retainers” extending up from the ends of the pier caps to provide lateral restraint of the edge girders were cracked and spalled, but did not fail, indicating that the bridge was loaded in the transverse direction. The shear keys on the western abutment pier cap were damaged in a similar manner. Transverse offset of the elastomeric bearings was also observed.
2. Flexural cracking was observed on the inward (river side) of the columns at the column-to-pile-cap connection of the piers on both sides of the river crossing. The flexural demand indicates horizontal movement of the foundations and pile cap towards the center of the river due to lateral spreading. The bridge deck was cracked above these damaged piers.
3. Vertical settlement of approximately 0.5m of one of the piers resulted in vertical displacement and cracking of the bridge deck immediately above the pier. This pier was adjacent to the span of the railroad bridge that collapsed, on the east river bank.

4.3 Performance Comparison

The desirable performance of the highway bridge appears to be due at least in part to the presence of the diaphragm anchorage blocks connecting the pier caps to the spans, which allowed the load acting on the foundations to be transferred to and resisted by the superstructure acting in compression along the longitudinal axis of the bridge. Lacking this positive structural connection, the railroad bridge piers had minimal translational restraint once the shear capacity of the elastomeric bearings was exceeded. The force exerted on the bridge foundations also differed due to the different layout and type of foundation elements. The highway bridge foundations may extend further into the dense sand layer, which would give them additional lateral resistance.

Although the reconnaissance team was not able to directly measure the lateral spreading deformation along the axis of the bridges due to ongoing repair efforts, it was visually evident that the deformation near the bridges was less than the measured deformation in the free field to the north and south. This indicates that the foundations of the bridges influenced lateral spreading soil displacements in the vicinity of the bridge. Furthermore, this indicates that the each bridge may have influenced the response of the other.

5. FURTHER RESEARCH

The authors plan to conduct cone penetration tests (CPT) at the site during the spring of 2013 in collaboration with the Mexican authorities in order to obtain detailed geotechnical data. Shear wave velocity and porewater pressure will be measured during the CPT.

The highway bridge will be analyzed using the finite element program OpenSEES (McKenna 1997) according to the Ashford et al. (2011) guidelines (i.e., the “PEER approach”), and the performance predicted by the analyses will be compared to the observed bridge performance. Foundation elements will be modeled as beam on nonlinear Winkler foundations using displaced p-y springs to model the ground deformation due to lateral spreading. The primary emphasis of the analyses will be to model the highway bridge that did not collapse.

6. CONCLUSIONS

Structural details of a pair of parallel bridges crossing the Colorado River are presented, with a description of their performance during the 2010 M_W 7.2 El Mayor-Cucapah Earthquake in Baja California, Mexico. The authors’ proposed geotechnical site investigations and analyses are described. Results of the modeling will be reported in future publications.

Acknowledgements:

The authors acknowledge support from Dr. Raúl Flores Berrones of the Mexican Institute of Water Technology (IMTA) and Luis Humberto Ibarrola Diaz, General Director of Technical Services at SCT for assistance in obtaining the bridge plans and coordinating site activities.

References:

Ashford, S.A., Boulanger, R.W., and Brandenberg, S.J. (2011), "Recommended Design Practice for Pile Foundations in Laterally Spreading Ground," Pacific Earthquake Engineering Research Center, Report No. PEER 2011/04, 44 p.

Geotechnical Extreme Event Reconnaissance (GEER) (2010) Stewart, J., Brandenberg S. (eds). “Preliminary Report on Seismological and Geotechnical Engineering Aspects of the April 4 2010 M_w 7.2 El Mayor-Cucapah (Mexico) Earthquake”, Report No. GEER-023, available: http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Baja%20California_2010/Baja_Cover_2010.html

Hough, S. E. and A. Elliot (2004), “Revisiting the 23 February 1892 Laguna Salada Earthquake,” *Bull. Seis. Soc. Amer.*, **94**(4), 1571-1578.

McKenna, F.T. (1997), "Object-Oriented Finite Element Programming: Frameworks for Analysis, Algorithms and Parallel Computing," PhD Thesis, Department of Civil

Engineering, University of California, Berkeley.

Meneses, J. (ed.), et al. (2010), "The El Mayor-Cucapah, Baja California Earthquake April 4, 2010, An EERI Reconnaissance Report," Earthquake Engineering Research Institute, Oakland, California. Available: http://www.eqclearinghouse.org/20100404-baja/general-information/eeri-recon-report

Secretaría de Comunicaciones y Transportes de México (SCT) (1998), "Puente San Felipito," Construction Plans, State Government of Baja California, Mexico, Ministry of Human Settlements and Public Works, Design by Sigma Ingenieria Civil S.A. de C.V., 6 sheets.

United States Geological Survey (USGS) (2010), "Magnitude 7.2 - Baja California, Mexico, 2010 April 04 22:40:42 UTC," Available: http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/ci14607652/.