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Bridge damage caused by liquefaction during the 22 April 1991 Costa Rica earthquake

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Abstract: Liquefaction-induced lateral spreads during the April 22, 1991 Costa Rican earthquake (magnitude 7.7), caused extensive damage to bridges in the highway and railway systems. Lateral displacements as great as 2 m pushed piles and abutments from under decks collapsing at least 7 bridges and severely damaging several others. In one instance, the highway bridge over the Rio Estrella, the foundation resisted ground displacements, which were as great as 2 m near the bridge. In addition, ground failures disrupted about 30 percent of the highway pavement and misaligned several sections of railway grade in lowland areas. This investigation documents ground displacements and related damage at one highway and three railroad bridge sites.

1 INTRODUCTION

At 15:57 pm local time, April 22, 1991, a large (M = 7.5) earthquake struck Limon Province, Costa Rica killing 53 people, injuring 198, and causing widespread damage to constructed works (EERI, 1991). In particular, the transportation system in Limon Province was devastated. Both rail and highway traffic was immediately obstructed due to widespread disruption of pavements and roadway grades and the collapse of several bridges. Most of the damage to the highway and railway systems was caused by liquefaction and consequent ground failure, primarily lateral spreading.

The purpose of this investigation was to document ground displacements and related damage caused by liquefaction. We surveyed three railroad and two highway bridge sites and estimated displacements at two additional sites (Figure 1). Because of space limitations, only three railway bridges and one highway bridge are described here.

We conducted a field studies between May 27 and June 6, 1991 (5 to 7 weeks after the earthquake). We used an electronic total station to measure distances and angles. We also used metric tapes to measure distances and displacements. From this data, we calculated ground and structural displacements and compiled topographic maps for the sites.

2. LIQUEFIABLE SEDIMENTS

Limon Province lies in the eastern part of Costa Rica in a geologic province dominated by a broad plain that gently slopes from the Cordillera de Talamanaca to the Caribbean Sea. The plain is dissected by several large and many small river valleys that broaden as they approach the coast. Most liquefaction occurred in alluvial and fluvial deposits that underlie river floodplains or in deltaic, lagoonal or estuarine deposits that underlie lowlands along the coast.

Within the epicentral region, liquefaction was rather pervasive in these lowland areas. For example, the EERI reconnaissance team (EERI, 1991) estimated that about thirty percent of the highway pavement in these areas was disrupted by fissures, scarps and ground settlements caused by liquefaction (Figure 2). Similarly, several segments of railway grade were misaligned by the ground movements. The greatest damage occurred river crossings, however, where bridge decks were thrust over abutments, piers shifted riverward, and fills settled as much as 2 m. These displacements and the consequent damage are the subject of this report.

3. Rio Matina Railroad Bridge

Southeast of the community of Matina, the railroad crosses the floodplains and channel of the Rio Matina on a 400-m long bridge. On each side of the river, the bridge over the floodplain is composed of five simply supported steel plate-girder sections resting on concrete piers. Over the main channel, the bridge consists of three truss sections resting on concrete caissons.

During the April 22 earthquake, liquefaction of sediments beneath the floodplains on both sides of the

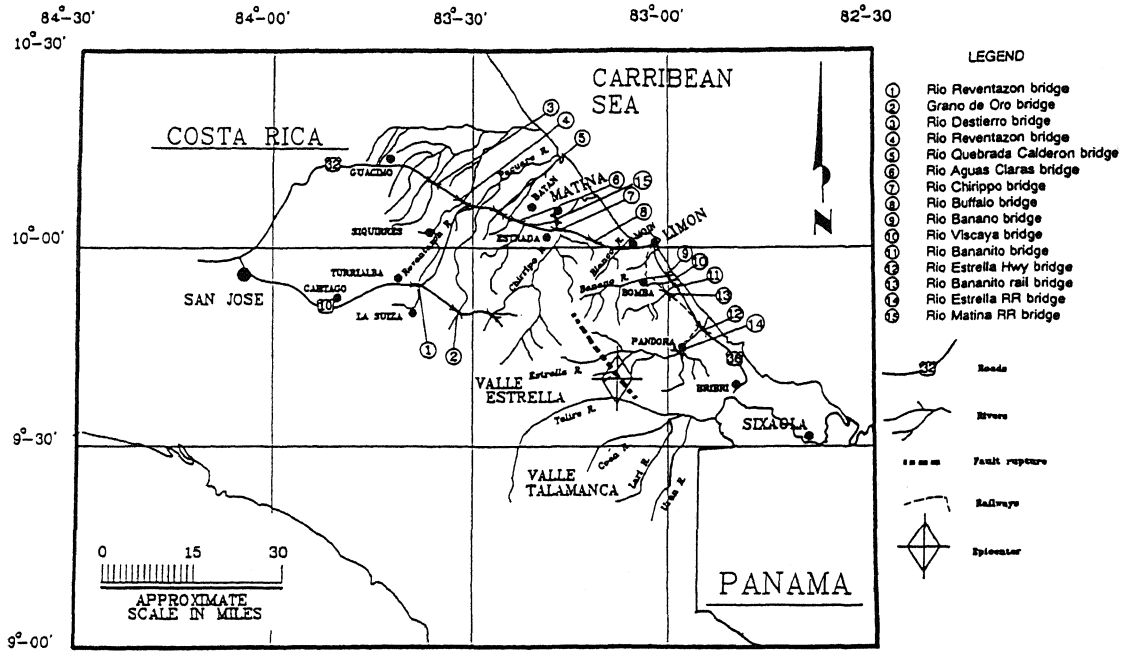

Figure 1. Map showing locations of damaged bridges and other pertinent localities. (Modified from EERI, 1991).

river caused the ground to spread laterally toward the incised river channel. These lateral displacements carried bridge piers and caissons toward the river causing several plate girder sections to drop off their supports and fall to the floodplain.

The truss sections were also pushed off their seatings on the caissons at the river banks, but the trusses did not tip or fall.

By the time of our visit, the railroad had been temporarily repaired by placing the plate girder sections on cribs of timber shoring and by releveling the truss and girder sections. In so doing, the rails had been restored approximately to their pre-earthquake elevations and alignment. This temporary repair allowed trains to cross the bridge at reduced speed and also provided a reference for us to measure displacement of the shifted piers. Figure 3 shows one of the timber shorings supporting plate girders and a measurement being made of the distance between a seating plate on the plate girder and its former anchorage on the shifted pier.

We conducted two surveys at the Matina bridge site. First, we used the realigned plate girders as a reference for measurement of horizontal and vertical pier displacements. Visual sighting of the rails across the bridge indicated that no major misalignment (more than a few centimeters) had occurred in realigning that structure, and hence our measurements are probably accurate within a few centimeters. Secondly, we conducted a topographic survey from which we

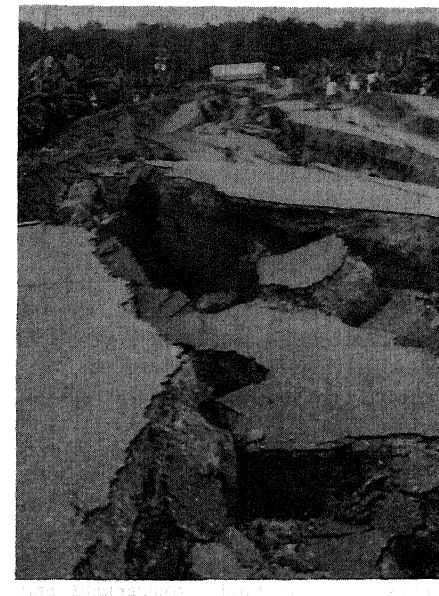

Figure 2. Highway pavement split and shattered by liquefaction-induced ground failure. A fallen truss of the Río Estrella highway bridge is visible in the background. View looking northward. (Photograph courtesy of Laboratorio de Ingenieria Sismica, University of Costa Rica)

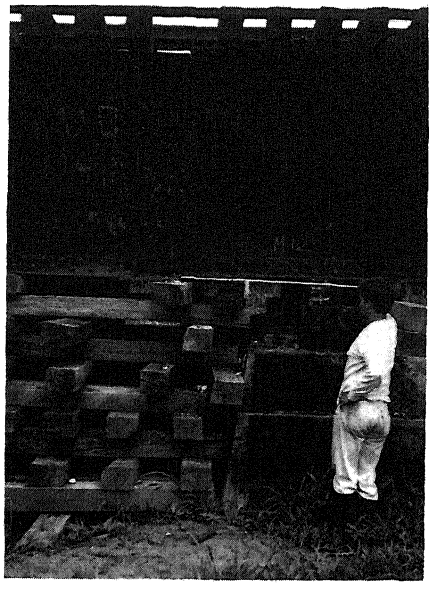

Figure 3. Bridge pier pushed 120 cm out from under plate girder bridge section that was reset on temporary shoring after the earthquake. (After EERI, 1991)

compiled a site map showing positions of bridge foundations, elevation contours, and major fissures and sand boils visible at the time of our investigation (Figure 4). Vectors on the figure show amounts and components of displacement for most of the bridge piers.

On the northwest side of the river, displacements increased riverward from 11 cm horizontal and 16 cm vertical at the abutment to 44 cm horizontal and 34 cm vertical at Pier M4, the pier nearest the river. On the southeast side of the river, horizontal displacements increased from 75 cm horizontal at the abutment to 120 cm at the Pier M12, the pier nearest the river. At each bank of the river, the girder-truss connections were supported on two 2.8-m diameter steel-lined and concrete-filled caissons. Each of those caissons tilted 4 to 5 degrees with the tops moving 66 cm and 120 cm riverward on the northwest and southeast sides of the river, respectively. Those displacements sheared the bridge connectors from the caisson, but the truss sections remained upright on the caisson. The floodplain soils pushed past the caissons on both sides of the river, leaving gaps as wide as one meter on the river sides of these shafts. The caissons also rocked back and forth during the earthquake as evidenced by circular voids as wide as 10's of centimeters the bases of the caissons. The floodplain soils also settled around the caissons by as much as 30 cm (Figure 5).

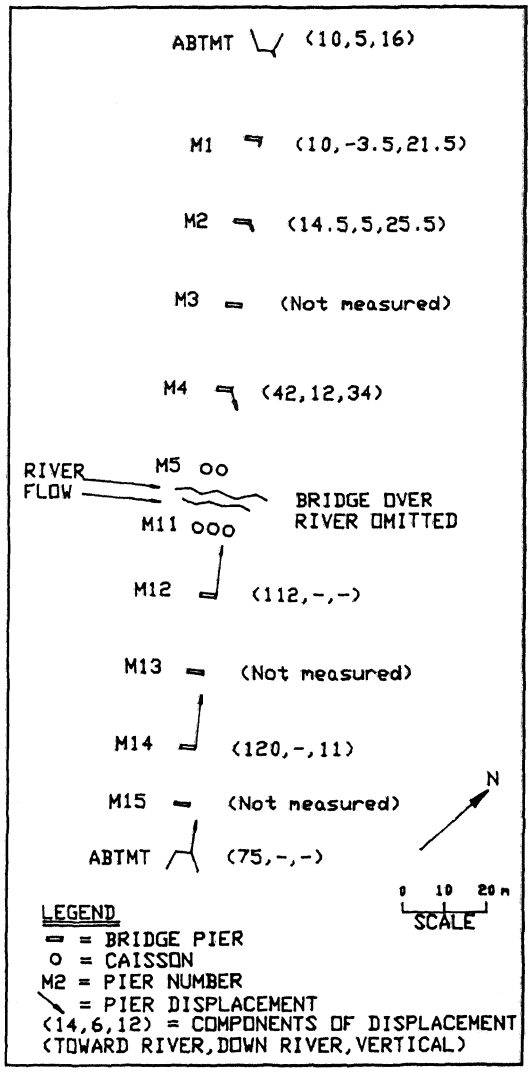

Figure 4. Map of railway bridge piers over floodplain of the Rio Matina. Vectors show pier displacements.

4. Rio Bananito Railway Bridge

The railway bridge over the Rio Bananito near Bananito Sur is a 50-m long, single-truss structure supported on elliptically-shaped caissons 1.46 m by 2.16 m across the major axes. The caissons are constructed of a 12 mm cast-steel shell filled with concrete. During the April 22 earthquake, ground displacements caused by liquefaction and lateral spreading pushed the supporting caissons out from under the seating plates on both ends of the bridge. This loss of support allowed the truss to tip downstream or eastward by about 15 degrees (Figure 6).

Figure 5. Caisson beneath Rio Matina Bridge that tilted by 4.5 degrees due to lateral ground displacement. Light ring at base shows amount of ground settlement. (After EERI, 1991)

We surveyed the site and measured caisson displacements beneath the bridge. At the northwest end of the bridge, the tops of the caissons shifted displaced 4.3 m and 5.7 m toward the river and the caissons were tilted 26 and 37 degrees, on northeast and southwest sides, respectively (Figure 7). The 0.9-m high capital on the north caisson pulled off during the earthquake and had fallen to the ground by the time of our visit. A concrete wall in the abutment had shifted 2.8 m toward the river and tilted slightly. These measurements indicate that lateral ground displacements beneath the north end of the bridge were between 2.0 m to 2.5 m.

Beneath the southeast end of the truss, the tops of the two supporting caissons were displaced 2.83 m and 1.90 m, respectively, with reference to seating plates on the truss. The greater displacement occurred on the northeast side, the direction in which the truss tilted. The caissons tilted toward the river 19 and 7 degrees, respectively. A retaining wall in the abutment shifted 1.43 m toward the river and tilted slightly. These measurements indicate that horizontal ground displacements beneath the southeast end of the bridge were between 1 m to 1.5 m.

5. Rio Estrella Railway Bridge

Figure 8 shows piers that previously supported part of the railway bridge over the Rio Estrella near Pandora. The bridge across the floodplain was constructed of simply-supported plate girder spans resting on the steel piers. The spans over the river are steel trusses supported on caissons. During the earthquake, permanent and transient ground and bridge displacements shifted and tilted the piers causing most of the plate girder sections to fall onto the floodplain.

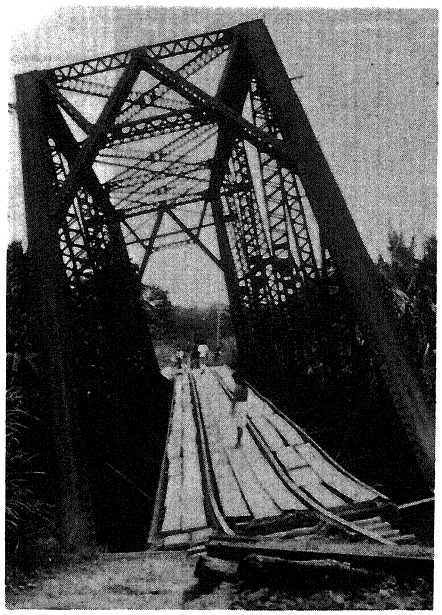

Figure 6. Railway bridge over the Rio Bananito that tipped due to caissons being pushed out from under bridge seatings. (Photograph courtesy of Laboratorio de Ingenieria Sismica, University of Costa Rica)

By the time of our visit, the piers had been uprighted by pulling on them with cables attached to the winch on a crane. As can be seen in Figure 8, when the piers were pulled back into a vertical position they were no longer in alignment nor were they equally spaced as they had been.

We surveyed the site to determine the positions of the uprighted piers. Assuming that the piers were

Figure 7. Caissons beneath the Rio Bananito railway bridge that tipped. Caissons were pushed laterally and tilted by as much as 5.7 m (at the top) and inclined by as much as 37 degrees.

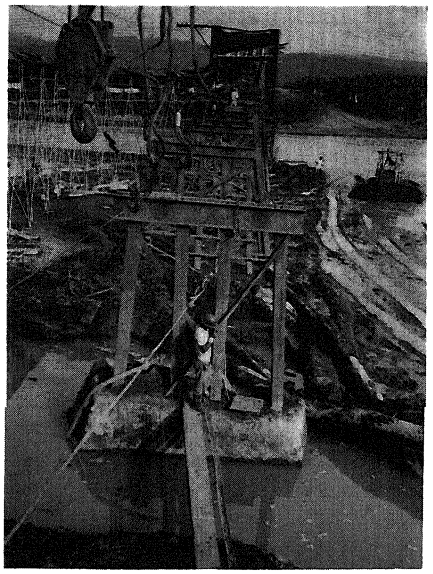

Figure 8. Piers for Rio Estrella railway bridge which tilted during the earthquake and later were uprighted but are out of alignment and no longer equally spaced. The pier nearest the camera shifted 0.8 m to the right; the next pier back shifted 0.8 m toward the camera.

equally spaced and in line before the earthquake, the survey data indicate that the pier nearest the camera in Figure 8 shifted about 0.8 m to the right (in an upstream direction) and the second pier back shifted about 0.8 m inland (away from the river). The other piers shifted as much as 0.15 m and some rotated clockwise a few degrees.

Fissures, as wide as 30 cm, and sand boils were found in the banana plantation northeast of the damaged bridge section. These features indicate that liquefaction and lateral spreading occurred in the vicinity of the bridge. By the time of our visit, however, any fissures or boils under the bridge had been obliterated by construction activities.

6. Rio Estrella Highway Bridge

The highway bridge over the Rio Estrella incorporated two 75-m long trusses and a 25-m long plate girder section. During the earthquake the ends of the two trusses fell from their common support and dropped into the river (Figure 9). Other damage at the site included spalling of concrete at the tops of the piles supporting the north abutment, and as much as 2 m settlement of the fill behind the south abutment (Figure 10). The roadway approach south of the bridge settled, broke up and spread laterally as a consequence of liquefaction of the underlying soils (Figure 2). During our survey, we walked through banana plantations near

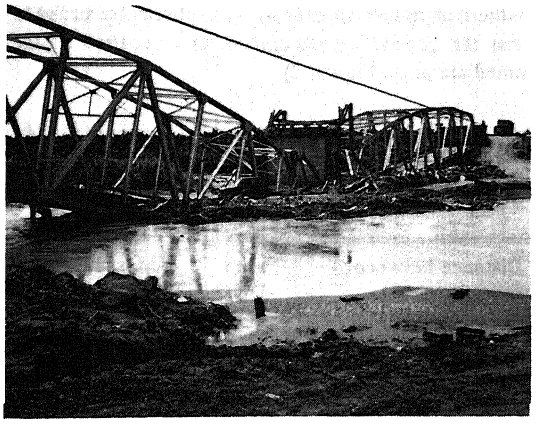

Figure 9. Truss sections that fell from the central pier of highway bridge over the Rio Estrella. Our survey indicates that these piers and abutments remained in their pre-earthquake positions even though the ground shifted toward the river around the south abutment. (After EERI, 1991)

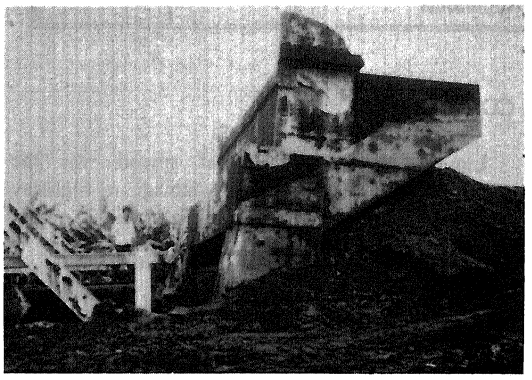

Figure 10. South abutment of the Rio Estrella highway bridge which remained in place even though the fill settled 2 m and nearby ground shifted more than 2 m. (Photograph courtesy of Laboratorio de Ingenieria Sismica, University of Costa Rica)

the south abutment and noted several large fissures, parallel to the river which are indicative of riverward ground displacements of up to 2 m.

We surveyed this site with an electronic total station to determine the positions of piers and abutments after the earthquake. We then calculated distances between these elements and compared them with distances listed on the bridge plans (Table 1). The differences between these distances fall within the range of expected survey and construction error and show that significant permanent displacement did not occurred between these components. In particular, the foundation for the

southern abutment apparently was sufficiently strong to resist the ground displacements that occurred in the immediate area (Figure 2).

Table 1. Comparison of plan and measured post-earthquake distances between bridge elements for the highway bridge of Rio Estrella. (After EERI, 1991)

Distance between center of bridge seats on:	Plan Distance m	Measured post-earthquake distance m
North Abutment and Pier 1	25.00	24.96
Pier 1 and Pier 2	75.00	75.02
Pier 2 and South Abutment	75.00	75.24
North and South Abutments	176.32	176.14

6. CONCLUSIONS

A. Liquefaction-induced lateral spread was the primary cause of extensive damage to highway and railway bridges during the April 22, 1991 magnitude 7.7 earthquake.

B. Lateral displacements as great as 2 m pushed piles and abutments from under decks causing collapse of at least 7 bridges and severe damage to several others.

C. In at least one instance, the highway bridge over the Rio Estrella, the foundation of a bridge abutment was sufficiently strong to resist ground displacements, which in the near vicinity were as great as 2 m.

D. Liquefaction, lateral spreading and ground settlement caused additional damage to the transportation system by shattering about 30 percent of highway pavements in lowland areas and by misaligning several railway grades.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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