Liquefaction-Induced Damage to Bridges

T. LESLIE YOUD

Liquefaction-induced lateral spread is a major cause of earthquake damage to bridges built across streams and rivers. Lateral spreads are characterized by horizontally displaced ground with extensional deformations at the head of the feature, shear deformations along the margins, and compressed ground at the toe. Displacements generally range from a few centimeters to several meters and are directed down mild slopes or toward a free face, such as an incised river channel. Such displacements thrust bridge abutments and piers riverward, generating large shear forces in connections and compressional forces in the superstructure. These forces have sheared connections, allowing decks to be thrust into, through, or over abutment walls or causing decks to buckle. In other instances, connections have remained intact with the deck acting as a strut, holding tops of piers and abutments in place while the bases of these elements are displaced toward the river. These actions have inflicted severe damage and even bridge collapse. The performance of bridges during past earthquakes is reviewed to illustrate types of damage as a consequence of liquefaction-induced ground displacement.

Liquefaction-induced ground failure is a major cause of earthquake damage to bridges. Bridges spanning rivers are particularly vulnerable to liquefaction because such structures commonly are founded on floodplain alluvium in areas with high groundwater levels. These conditions—recent deposition and high groundwater—are characteristics of sediments with high liquefaction susceptibility. Floodplain topography—including gentle slopes and incised river channels—is characteristic of areas susceptible to liquefaction-induced lateral spread.

Lateral spreads (Figure 1) are characterized by ground displacement down mild slopes or toward a free face, such as an incised channel. Lateral displacements may range from a few centimeters to several meters and are generated by a combination of gravitational and seismic forces. Bridge piers and abutments founded on a lateral spread are usually transported riverward with the spreading ground. Consequent differential displacements between foundation elements create severe stresses, deformations, or both within the bridge structure. To illustrate and categorize the types of damage inflicted by lateral spreads, several case histories of bridge damage are reviewed.

BRIDGE DAMAGE DURING PAST EARTHQUAKES

Hayward, California, 1868

One of the first instances of bridge damage caused by liquefaction-induced lateral spread in the United States apparently occurred during the 1868 Hayward, California, earthquake. Halley (*2*) noted the following: "The drawbridge on the line of the S.F. and O.R.R. was thrown out of place about eight inches [0.2 m], and as the locomotive and nearly all the cars were at San Antonio, no train left Oakland at 8 o'clock." This description is not very clear, but the type of damage—compression of the bridge structure—is typical of damage inflicted by lateral spread.

Charleston, South Carolina, 1886

The evidence is more explicit that liquefaction-induced lateral displacement damaged several bridges during the 1886 Charleston, South Carolina, earthquake. For example, Earle Sloan [quoted by Peters and Hermann (*3*)] penned the following cryptic notes concerning the Bacous bridge over the Ashley River: "[The damage] affords evidence of tendency of banks to approach centre of channel. Here expressed by compression of bridge causing one plank to overlap another seven inches [0.18 m] and jamming joints." The same investigator gave the following description of the railroad bridge over Rantowles Creek:

> Close inspection revealed fact that there had been a vibratory movement of sufficient energy to have caused entire [word missing] plastic earth with included piling on each side of "draw" to bodily approach channel of stream; the piling which affords no indication of relative movement from enclosing earth has dragged attached bents from vertical position and jerked superstructure from opposite sides to center line with a violence wrecking rails, bulging up stringers, forcing up caps of bents, mortised and spiled with 4 inch tenons, to top of latter, and in general affording liberal indications of shortening of distance separating the banks. Superstructure on both sides of "draw" was violent flexured both transversely and vertically with accumulated length of rail. Latter accumulation accounted for by near summit of involved grade where joints are liberally parted. (*3*)

These descriptions document lateral movements and the damage they caused. Ground displacements as great as several tenths of a meter shifted abutments and piers toward the centers of the channels, compressing bridge decks with attendant bulging up of stringers and overlapping of planks. Documented ground disturbances—including ground fissures and sand boils—confirm that liquefaction was widespread near these bridges.

San Francisco, California, 1906

Lateral spreads generated by the 1906 San Francisco earthquake damaged several bridges, including the highway bridge over the Salinas River south of Salinas, California (Figure 2).

Department of Civil Engineering, Brigham Young University, Provo, Utah 84602.

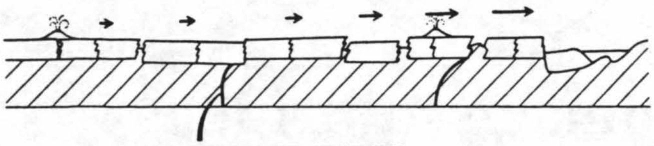

FIGURE 1 Diagram of a lateral spread showing liquefied layer, ground displacement, and disrupted ground surface [after National Research Council (*1*)].

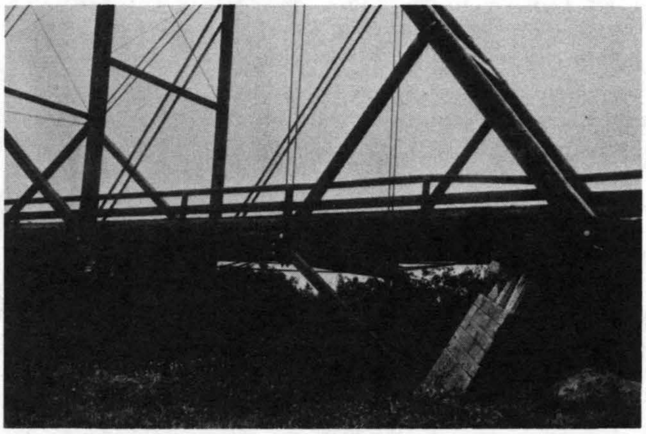

FIGURE 2 Highway bridge over Salinas River south of Salinas, California, that was damaged by lateral ground displacement during the 1906 San Francisco earthquake. The ground displacement physically moved the base of the southern pier 2.8 m toward the river (*photograph by J. C. Branner, courtesy of Stanford University Archives*).

Lateral displacement of the floodplain physically displaced both ground and pile foundation about 1.8 m northward toward the river channel. The bridge trusses and deck were strong enough to remain intact and were essentially undamaged. The deck, which remained attached to the tops of the piers, acted as a strut, holding the tops of the piers in place while their bases shifted riverward. This motion left the southern pier inclined, with the top of the pier tilted outward, away from the river.

Prince William Sound, Alaska, 1964

The most devastating earthquake damage to bridges in U.S. history occurred during the great Alaskan earthquake of 1964. Liquefaction and lateral spread damaged 266 railway and highway bridges, collapsing about 20 and damaging many others beyond repair. This destruction severely impaired the surface transportation system in southern Alaska for many months after the earthquake.

In nearly all instances, the Alaskan bridges were compressed as a consequence of lateral ground displacement. Those displacements inflicted different types of damage, depending on the amount of ground displacement, the strengths of various structural elements, and the orientation of the bridge relative to the river. The general types of damage are discussed in the following sections.

Railway Bridges

According to McCulloch and Bonilla (*4*), 125 railway bridges and 110 culverts were damaged or destroyed during the 1964 Alaska earthquake. None of those bridges collapsed, although many were irreparable and had to be replaced. The estimated cost to repair and replace these structures was about $2.5 million (1964 dollars). For comparison, the cost to regrade, repair, and realign railway embankments, which were also severely affected by ground failure and ground subsidence, was nearly $9 million. McCulloch and Bonilla recorded the following general description of ground displacements and consequent damage to railway bridges, most of which were timber structures:

> In all but six bridges, the net compression shown by interbent measurements exceeded the net extension. Net compression was generally 20 inches [0.50 m] or less, regardless of bridge length, but in two bridges compression was as large as 64 and 81.5 inches [1.62 and 2.07 m]. . . . In addition to having their supporting bents torn free, most stringers were put into compression by converging streambanks. Distances between streambanks were decreased by as much as 6.5 feet [2.0 m]. As a result, the stringers acted as struts, and either jammed into the fillers on the bulkheads or, where compression was greater, drove through the bulkhead planks. In some bridges most of the compression was released at one end, and the stringers were thrust up over the top of the bulkhead onto one of the approach fills. . . . Compressive forces not released by failures at the bulkheads produced lateral deflections in the decks of several bridges. Stringers were either thrown into long horizonal bends, or were broken at sharp kinks, with as much as 8 feet [2.4 m] of lateral deflection at the apex of the bends. (*4*)

The following examples of damaged railway bridges illustrate these effects. The damage to the bridge at Milepost 61.9 is representative of stringers thrust through bulkhead walls (Figure 3). This bridge consisted of seven 4.5-m long spans supported on interior timber pile bents with timber bulkheads at either end. About 0.5 m of streambank convergence compressed the bridge structure, tearing stringers from their seatings and thrusting the loosened stringers through the bulkhead walls.

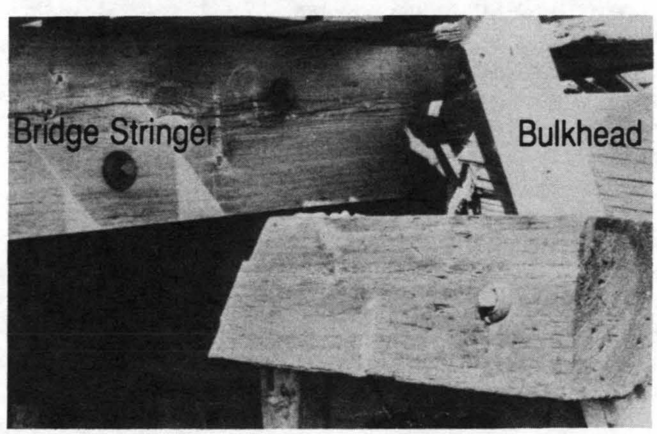

FIGURE 3 Stringers of Bridge 61.9 that were driven though the bulkhead wall by convergence of the stream banks during the 1964 Alaska earthquake [after McCulloch and Bonilla (*4*)].

A similar type of failure occurred to a highway bridge over one of the channels of the Resurrection River near Seward. The banks of the river spread into the channel, causing more than 0.3 m of convergence between bridge abutments (Figure 4). The narrowing of the channel thrust the bridge girders and deck into the abutment wall, which fractured and rotated under the impact, allowing the deck to penetrate about 0.3 m into the adjacent fill. The ground displacement carried the adjacent bridge pier about 0.3 m toward the channel, with the top of the pier remaining attached to the deck. As shown in Figure 4, this displacement fractured the pier at the ground line and tilted the upper part of the pier outward, away from the river.

The bridge at Milepost 37.3 is representative of a structure that fractured and buckled because of compressional forces applied by the converging stream banks (Figure 5). This bridge was composed of five 4.5-m long spans. The stream banks converged about 0.18 m, causing the deck to buckle horizontally by about 1.2 m (*4*). A few similarly stressed bridge decks buckled upward rather than laterally.

Bridges that crossed streams at oblique angles commonly skewed, rather than buckled, under ground-induced compressional forces. For example, the railway bridge at Milepost 63.0 (Figure 6) skewed horizontally as a consequence of about 2.8 m of stream bank convergence. The bridge was a 58.4-m long structure supported by 14 pile bents. The convergence of the stream banks shifted the pile bents streamward on both sides of the channel. Because the direction of ground displacement was at an angle to the longitudinal axis of the bridge, the compressional forces generated horizontal forces between the deck and the southern bulkhead. These forces fractured the stringer connections at the bulkhead and deflected the deck 2.4 m eastward (to the right in Figure 6). The deck rotated and bowed horizontally as a unit, breaking connections between some pile caps and stringers and dragging others laterally with the displaced deck.

In their field investigations, McCulloch and Bonilla (*4*) found no instances in which piles had sunk to greater depths than their pre-earthquake positions. Conversely, in several instances the piles had risen. McCulloch and Bonilla attribute that rise to lateral spread of the ground toward river channels, which compressed sediments within the channels, causing channel beds to heave upward and lift the piles with the rising soil. Buoyancy of the piles and upward pull by arching superstructures also may have contributed to the upward movement.

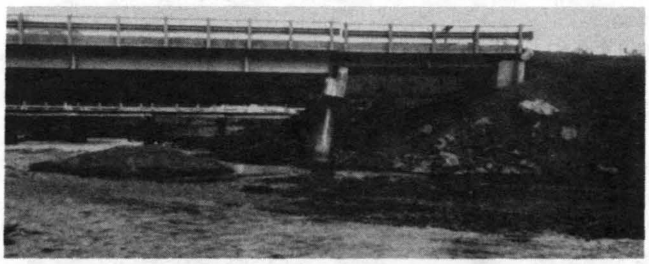

FIGURE 4 Highway bridge over Resurrection River that was compressed by lateral spreading during the 1964 Alaska earthquake. The compression thrust the deck into and fractured the abutment wall, and ground displacement carried the adjacent pier streamward, fracturing that element at the ground line [after McCulloch and Bonilla (*4*)].

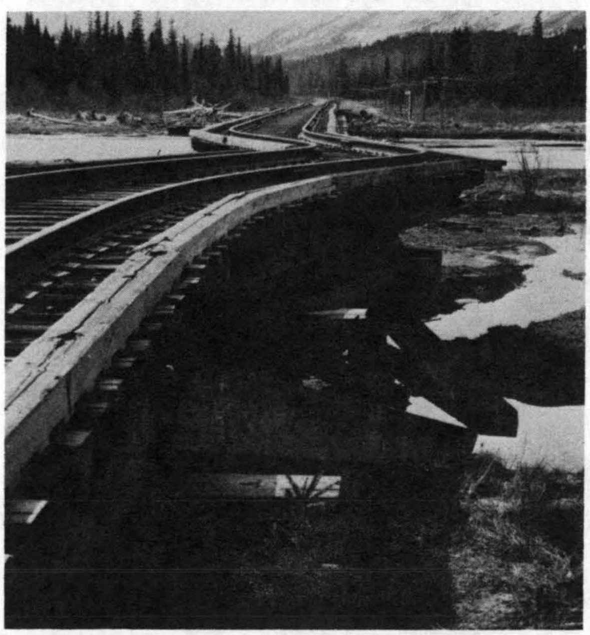

FIGURE 5 Deck of the Alaska railway bridge at Milepost 63.0 buckled by stream bank convergence of about 0.18 m [after McCulloch and Bonilla (*4*)].

Highway Bridges

Highway bridges were affected even more severely than railway bridges during the 1964 earthquake. Kachadoorian (*5*) classified more than 20 highway bridges as destroyed, by which he generally meant that foundations had failed and decks had collapsed. Nearly all of this destruction was caused by lateral displacement of piers and abutments. These displacements

FIGURE 6 The Alaska railroad bridge at Milepost 63.0 that was compressed by lateral ground displacement, causing near end of the bridge to shear connections with the bulkhead and skew to the right [after McCulloch and Bonilla (*4*)].

broke connections with the superstructure, leaving decks unsupported. One collapsed bridge—the structure over Twentymile River—is shown in Figure 7. This and other severely damaged bridges were at localities of intense liquefaction effects—including ground oscillation and lateral spread—as described by Kachadoorian (*5*):

> The seismic shaking and lateral displacement of the sediments pulled the wood ties off the caps, and the superstructure became independent of the substructure. The deck or superstructure had a vertical as well as a horizontal component of movement during the earthquake. Eventually the wood bents failed beneath the superstructure and the bridge collapsed. In many bridges the wood piles were driven through the reinforced concrete deck [Figure 7]. Eye witness reports show that the decks had an up-and-down motion period of about 1 second. That is, a wave apparently passed through the deck, and, as it passed through, the superstructure moved up and down in about a 1-second cycle. (*5*)

Kachadoorian then indicates that the up-and-down motions caused impacts between the piles and bridge decks (after the pile caps had failed) that drove the piles through the deck.

This description of bridge failure indicates that seismic shaking liquefied the underlying soils, which in turn spread laterally toward the river channel. That ground movement pushed the pile bents riverward, shearing connections with the superstructure. The ground apparently did not move in a single uniform motion, but oscillated back and forth and up and down in waves as it migrated toward the river. This oscillatory movement caused the bridge deck to vibrate vertically—and apparently out of phase with the underlying ground—generating intense impacts between the deck and the detached piles, with the piles eventually punching through the paved surface as the deck fell to the ground.

In addition to bridges classified as "destroyed," Kachadoorian classified more than 70 bridges as severely damaged. Such a rating generally meant that abutments and pile bents shifted horizontally, breaking connections with superstructure. This action was accompanied by ramming of decks into abutment walls, severely damaging either stringers or trusses or the abutment, as shown in Figure 3. However, none of the severely damaged bridges collapsed.

With respect to postearthquake pile elevations, Kachadoorian (*5*) noted that after the earthquake, most of the piles beneath destroyed or severely damaged highway bridges were lower, but by no more than about 0.1 m. The reason for this penetration of piles is not given, but it may have been caused by pounding of the deck. This small amount of settlement indicates that major loss of pile-bearing resistance did not occur.

In total, Kachadoorian (*5*) classed 92 highway bridges (45 percent of those in the heavily shaken area) as destroyed or severely damaged. An additional 49 bridges (24 percent of the total) were classed as slightly to moderately damaged. The estimated cost to repair or replace these structures was more than $25 million (1964 dollars). The tenfold-greater monetary damage to highway bridges compared with railway bridges indicates the greater destruction to the highway structures.

Niigata, Japan, 1964

Three months after the 1964 Alaskan earthquake, a large earthquake struck the west coast of Japan near the city of Niigata. That earthquake generated some of the most widespread and spectacular effects of liquefaction of any modern earthquake. The combined effects of the 1964 Alaska and Niigata earthquakes forcefully drew the world's attention to the destructive capability of liquefaction; rigorous studies of the liquefaction phenomenon were initiated immediately thereafter. Liquefaction-induced lateral spread during the Niigata earthquake caused bank convergence of as much as 23 m across the 250-m wide Shinano River (*6*). Those displacements severely damaged one railway and three highway

FIGURE 7 Collapsed highway bridge across Twentymile River (bridge nearest camera); a damaged but intact railway bridge is behind highway structure [after McCulloch and Bonilla (*4*)].

bridges. For example, several deck segments of the Showa highway bridge collapsed into the river as a consequence of ground displacement (Figure 8). Hamada and others (*6*) give the following description of that collapse:

> There were obvious signs that a violent collision had occurred between the girders themselves and the abutment on the left bank. From the above, it can be conjectured that a large horizontal force had been exerted on the girder from the abutment on the left bank, and this is considered to have been one of the causes of the collapse. There were also signs that the bridge pier foundations on the left bank had moved toward the center of the river. In particular, pier P_6 had tilted considerably toward the right bank. It may be considered that such movement of the bridge pier foundations also contributed to the collapse. (*6*)

The steel-pipe piles supporting another pier, P_4 (located within the river), were extracted and examined after the earthquake. The deformed shapes of those piles indicate that about 0.5 m of lateral displacement had occurred at the level of the river bed and that ground displacement reached depths as great as 7 to 8 m below the bed.

As noted by Hamada and others, horizontal displacement of the piers supporting the Showa bridge was much less than displacement of the ground a short distance either upstream or downstream from the bridge. This reduced displacement indicates that the bridge restrained ground deformation. Other bridges across the Shinano River impeded lateral ground movements as well. In the latter instances, the decks remained attached to the piers and acted as struts or braces, increasing resistance to ground displacement. For example, a postearthquake aerial photograph (Figure 9) shows reconstructed river revetments above and below the Bandai Bridge. Those revetments formed a straight line before the earthquake. The revetments were pushed toward the river during the earthquake and then reconstructed in their postearthquake position. The reduced ground displacement near the bridge is graphically illustrated by the landward curvature of the reconstructed revetments. Further evidence that the bridges restricted bank displacements is given by Hamada and others (*6*), who calculated vectors of ground displacement from photogrammetric analyses of pre- and postearthquake aerial photographs. Those vectors indicate that river bank displacements were about 8 to 9 m upstream from the Bandai Bridge, but only about 4 to 5 m near the bridge. Thus the bridge apparently restrained lateral ground movements by about 4 m.

FIGURE 8 Showa highway bridge that collapsed into the Shinano River during the 1964 Niigata, Japan, earthquake (*photograph by T. L. Youd*).

Limon Province, Costa Rica, 1991

During the April 22, 1991, earthquake in Limon Province, Costa Rica, eight major highway and railway bridges collapsed, and several other bridges were severely damaged. All of these bridges were at river crossings and in nearly all instances, liquefaction-induced ground displacement was the cause of damage.

The modes of bridge damage in Costa Rica were generally similar to those described above; that is, lateral displacement of floodplain deposits pushed abutments and piers riverward, shearing connections and causing other damage. In several instances, however, the connections between the foundation and the deck sheared readily, preventing the deck from acting as a strut or brace. The connection failures allowed the abutments and piers to readily shift or tilt toward the river channel, removing support from the superstructure. An example of this type of failure is illustrated by the tipped railroad bridge over the Rio Bananito near Bananito Sur (Figure 10). The steel-truss single-span bridge was supported by four 1.5 m by 2.1 m oval-shaped concrete caissons, one placed under each corner of the truss. Liquefaction and lateral spread on both sides of the river pushed the tops of the caissons inward (Figure 11), removing support from the truss, which then dropped and tilted downstream. Displacements of the tops of the caissons ranged from 1.9 to 5.7 m (*7*).

The highway bridge over the Rio Estrella is of interest because although the superstructure collapsed, the foundation did not permanently displace. The bridge was composed of one 25 m long plate girder section and two 75 m long truss sections. During the earthquake, the two trusses fell from their common support on a central pier and dropped into the river (Figure 12). Simultaneously, the roadway approach to the south end of the bridge settled about 2 m, broke up, and

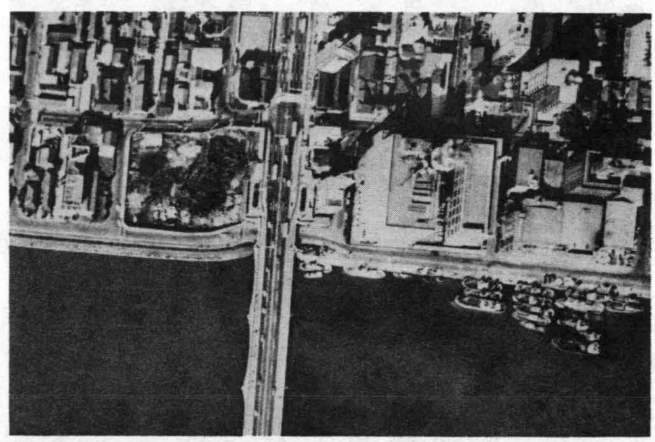

FIGURE 9 Aerial view of Bandai Bridge showing curved revetments along water-bank interface. The curvature was caused by lateral ground displacements during the 1964 Niigata earthquake [after Hamada et al. (*6*)].

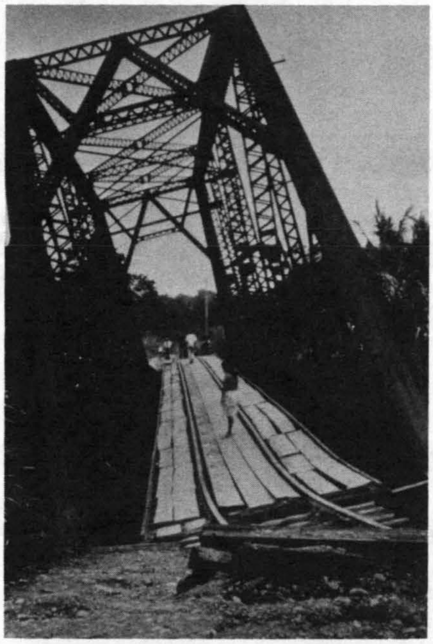

FIGURE 10 Railway bridge over the Rio Bananito that tipped during the 1991 Costa Rican earthquake; lateral ground displacement pushed the supporting caissons from the bridge seatings leaving the truss unsupported (*photograph courtesy of Laboratorio de Ingeniria Seismica de la Universidad de Costa Rica*).

FIGURE 11 Caissons beneath the Rio Bananito railway bridge that were pushed riverward by lateral ground displacement during the 1991 Costa Rica earthquake (*photograph by T. L. Youd*).

spread laterally (Figure 13). Large fissures parallel to the river developed in banana plantations on either side of the approach road. These effects indicate that liquefaction and lateral spread were widespread near the southern abutment.

Youd et al. (*7*) surveyed the bridge site after the earthquake and compared measured distances with those noted on the bridge plans (Table 1). Differences between the pre- and postearthquake distances were small and fall within the range of survey and construction error. These comparisons indicate

FIGURE 12 Highway bridge that collapsed into the Rio Estrella during the 1991 Costa Rica earthquake (*photograph by T. L. Youd*).

FIGURE 13 Liquefaction-induced settlement and deformation of approach fill adjacent to southern abutment of Rio Estrella highway bridge (*photograph courtesy of Laboratorio de Ingeniria Seismica de la Universidad de Costa Rica*).

that the abutments and piers withstood earthquake shaking and the development of liquefaction without significant permanent displacement. In particular, the foundation beneath the southern abutment remained in place, even though liquefaction and substantial ground disruption occurred in the immediate vicinity (Figure 13). This abutment consisted of a concrete wall supported on two substantial groups of piles, which extend to depths of about 14 m below river level (*8*).

PREDICTION OF GROUND DISPLACEMENT AND BRIDGE DAMAGE

Two pieces of information are required to determine bridge safety against ground failure: an estimate of ground displacement and an assessment of bridge capability to withstand that displacement. Some progress has been made over the past few years in developing techniques for evaluating ground displacement. Case histories have been compiled from which the primary factors controlling displacement have been identified and regression analyses have produced predictive models (*9*). Several investigators have also applied analytical techniques to estimate ground movements, but more development and

TABLE 1 Comparison of Plan and Measured Postearthquake Distances Between Bridge Elements for the Highway Bridge over Rio Estrella (8)

Distance Between Centers Of Bridge Seats On:	Plan (m)	Post-Earthquake (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

verification of those techniques are required. The second component, assessment of the capability of bridges to resist ground displacement, is practically unstudied. Likewise, the effectiveness of remedial measures that might be used to strengthen bridges or to stabilize the ground to resist displacement has not been widely researched. It is beyond the scope of this paper to discuss these topics further except to note that much more research attention is required to develop engineering guidelines for design or retrofit of bridges to withstand liquefaction-induced ground displacements.

CONCLUSIONS

The following conclusions were reached as a result of this study:

1. Lateral spread has been the primary cause of liquefaction-induced damage to bridges. Lateral ground displacements physically have moved abutments and piers riverward, creating large shear forces at connections and compressional forces within the superstructure.

2. Compressional forces generated by lateral ground displacement generally cause one of the following reactions:

a. The superstructure may act as a strut, bracing tops of abutments and piers and holding them relatively in place while the bases of these elements shift streamward with the spreading ground. This action leaves piers and abutments tilted outward away from the river.

b. The connections between the foundation and the superstructure may fail, allowing piers and abutments to shift or tilt toward the river with little restraint. In this instance, the deck may strike the backwall of the abutment, which may either fracture the wall and allow the deck to penetrate into the embankment or deflect the deck upward and over the abutment and embankment.

c. The deck may buckle laterally or vertically, causing severe damage to the superstructure.

3. Only limited study has been made of bridge damage caused by ground displacement or of mitigative measures to prevent such damage. More research is needed on this topic.

REFERENCES

1. National Research Council. *Liquefaction of Soils During Earthquakes.* National Academy Press, Washington, D.C., 1985.
2. Halley, W. *The Centennial Year Book of Alameda County, California.* Oakland, 1876.
3. Peters, K. E., and R. B. Hermann. *First-Hand Observations of the Charleston Earthquake of August 31, 1886, and Other Earthquake Materials.* Bulletin 41, South Carolina Geological Survey, 1986.
4. McCulloch, D. S., and M. G. Bonilla. *Effects of the Earthquake of March 27, 1964, on the Alaska Railroad.* Professional Paper 545-D. U.S. Geological Survey, 1970.
5. Kachadoorian, R. *Effects of the Earthquake of March 27, 1964, on the Alaska Highway System.* Professional Paper 545-C. U.S. Geological Survey, 1968.
6. Hamada, M., S. Yasuda, R. Isoyama, and K. Emoto. *Study on Liquefaction Induced Permanent Ground Displacements.* Association for the Development of Earthquake Prediction, Tokyo, Japan, 1986.
7. Youd, T. L., K. M. Rollins, A. F. Salazar and R. E. Wallace. Bridge Damage Caused by Liquefaction During the 22 April 1991 Costa Rica Earthquake. *Proceedings, 10th World Conference on Earthquake Engineering,* Madrid, Spain, 1992, Vol. 1, pp. 153–158.
8. Earthquake Engineering Research Institute. Costa Rica Earthquake Reconnaissance Report. *Earthquake Spectra,* Vol. 7, Supplement B, Oct. 1991.
9. Bartlett, S. F., and T. L. Youd. *Empirical Prediction of Lateral Spread Displacement.* Technical Report NCEER-92-0021. National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1992.

Publication of this paper sponsored by Committee on Engineering Geology.