

APPENDIX

**LIQUEFACTION DAMAGE TO BRIDGES
AND APPROACH EMBANKMENTS:
CATALOG OF SELECTED CASE HISTORIES**

INTRODUCTION

The following catalog documents the seismic performance of bridges and ancillary components in the presence of liquefaction-induced ground displacements. Data pertaining to seismological, geotechnical, and structural aspects of numerous case studies are presented in order to facilitate the development of empirical guidelines for the identification of vulnerable foundation and bridge elements.

Each bridge in this catalog has been assigned a subjective damage severity rating (DSR) according to the classification scheme outlined in Table A.1. The classification scheme was developed in order to categorize bridge foundation displacements and the resulting damage into four degrees of severity. This classification scheme does not explicitly provide a causal relationship between the various seismic hazards and the mode of observed damage, it is however useful for documenting the pertinent characteristics of the earthquakes, site characteristics and the associated damage.

Table A.1: Foundation Displacement Classification Scheme

DAMAGE SEVERITY RATING (DSR)	DAMAGE DESCRIPTION
DSR = 3	Severe Damage: Abutments moved streamward and/or markedly subsided; piers shifted, tilted, settled, or fell over. Large movements of foundation units. Substructure rendered unsalvable.
DSR = 2	Moderate Damage: Distinct and measurable net displacements as in previous category but to a lesser degree, so that the substructure could perhaps be repaired and used to support a new superstructure.
DSR = 1	Minor Damage: Evidence of foundation movements such as cracked backwalls, split piles, and closed expansion devices, but net displacements small and substructure serviceable. Minor abutment slumping.
DSR = 0	Nil Damage: No evidence of foundation displacements.

The Damage Severity Indexes for selected bridges have been plotted as a function of earthquake magnitude and the distance from the earthquake source to the bridge site (Figure A.1). This general plot accounts, in an approximate manner, for the intensity of ground shaking and the duration of the motions. The bridge catalog includes an array of structures of various age, design and construction, therefore the relationship demonstrated in this figure provides only a very general view of bridge performance.

The two curves superimposed on Figure A.1 represent lateral spread displacements (D_h) of 305 mm (12 in) and 610 mm (24 in), computed using the empirical relationship of Bartlett and Youd introduced in Chapter 4. On the basis of the data obtained in this study it appears that the curve for lateral spread displacements of 0.3 m (1 ft) can be used as an approximate source-to-site boundary of damage/no damage in preliminary, system-wide screening evaluations of liquefaction hazards to bridges. It should be noted that several case studies demonstrated extensive bridge

damage at source-to-site distances greater than that indicated for 0.3 m (1 ft) displacement. This could be due to several factors (e.g., uncertainty in the Bartlett and Youd procedure, unique site effects, poorly designed or constructed bridges). Variables such as these must be evaluated in site-specific hazard analyses.

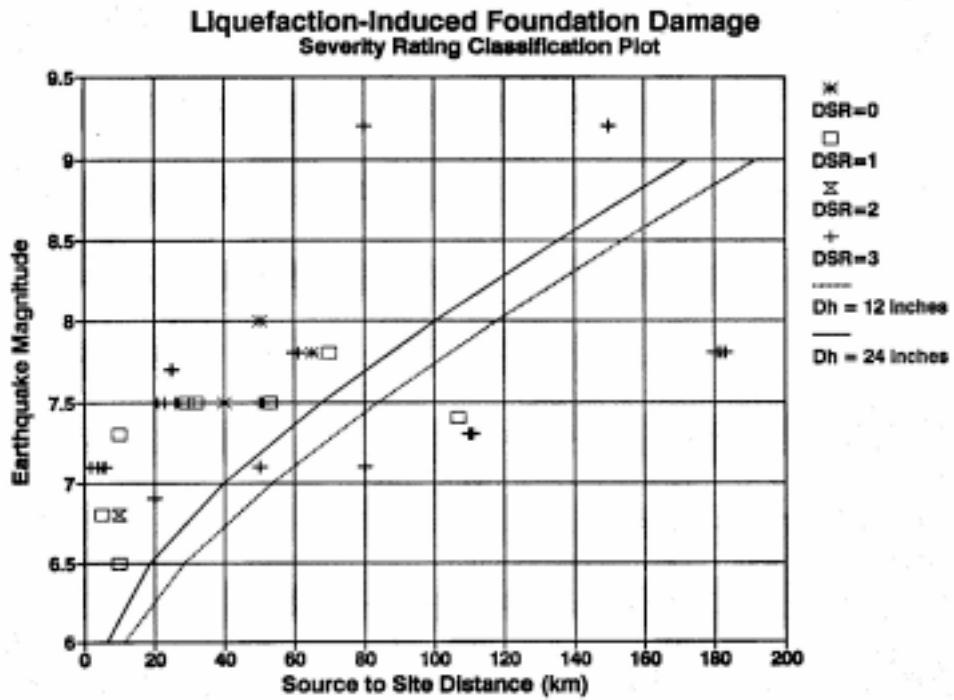


Figure A.1: Bridge damage as a function of earthquake magnitude and source-to-site distance.

EARTHQUAKES REVIEWED IN THIS INVESTIGATION

Background information about the following earthquakes can be found in this appendix.

1995	Manzanillo, Mexico, Earthquake	A-4
1995	Hyogo-ken-Nanbu (Kobe), Japan, Earthquake	A-5
1994	Northridge Earthquake	A-8
1994	Mindoro Island, Philippines, Earthquake	A-9
1993	Island of Guam Earthquake	A-10
1993	Hokkaido Nansei-oki, Japan, Earthquake	A-11
1992	Erzincan, Turkey, Earthquake	A-13
1991	Costa Rica Earthquake	A-14
1990	Luzon, Philippines, Earthquake	A-19
1989	Loma Prieta Earthquake	A-21
1983	Nihonkai-Chuba Earthquake	A-23
1980	El-Asnam, Algeria, Earthquake	A-24
1979	Imperial Valley, California, Earthquake	A-25
1978	Miyagi-Ken-oki, Japan, Earthquake	A-26
1976	Mindanao, Philippines, Earthquake	A-27
1976	Tangshan, China, Earthquake	A-28
1975	Haicheng, China, Earthquake	A-30
1968	Ebino Earthquake	A-32
1964	Alaska Earthquake	A-33
1964	Niigata, Japan, Earthquake	A-35
1948	Fukui, Japan, Earthquake	A-37
1923	Kanto, Japan, Earthquake	A-39
1906	San Francisco Earthquake	A-41
1886	Charleston, South Carolina, Earthquake	A-45

1995 MANZANILLO, MEXICO, EARTHQUAKE

Date of Occurrence: October 9, 1995

Magnitude: $M_S = 7.6$, $M_W \approx 7.5$

Location: The epicenter was located 20 km southeast of Manzanillo at a depth of about 30 km. Manzanillo is about 550 km west of Mexico City.

Reference: (1)

General Damage to Bridge Structures:

- Two prestressed concrete continuous bridges with 25 to 30 m spans suffered damage to the abutments due to soil failure. The bridges, on the Mexico 200 highway about 5 to 10 km outside the city of Manzanillo, remained open to traffic at reduced speed.

Distance to Epicenter (both bridges), **$R \approx 25$ km**

Damage Severity Rating, **$DSR = 1$**

1995 HYOGO-KEN NANBU EARTHQUAKE

Date of Occurrence: January 17, 1995
Magnitude: $M_W = 6.9$, $JMA = 7.2$
Location: The hypocenter was located about 20 km southwest of downtown Kobe, Japan between the northeast tip of Awaji Island and the mainland. The rupture length was inferred to have been in the range of 30 to 50 km with a focal depth of about 10 km.
Reference: (2), (3), (4) and (5)

General Observations:

The Harbor Highway suffered major damage during the earthquake. The area along the coast was subject to severe liquefaction and large soil movements. Much of the Harbor fell into the sea, consequently bridge foundations had less resistance from weak soils and rocked and displaced during the earthquake. Bridge superstructures fell off their bearings and in some cases off their substructure. Every bridge on the Harbor Highway from Nishinomiya to Rokko Island suffered this damage and the highway was closed after the earthquake. There was damage at almost every expansion joint along Harbor Highway; the entire highway was closed from Nishinomiya to Rokko Island. This damage was the result of bearing failures and large pier movements. Other damage included approach settlements and shattered piers along the harbor. Harbor Highway was a relatively new route with modern bridge structures. Large pier displacements were not anticipated or designed for, resulting in partial collapse and bridge closures.

Nishinomiya-Ko Arch Bridge: Harbor Highway, Route 5
Distance to Epicenter, $R \approx 20$ km
Damage Severity Rating, $DSR = 3$

Structure: Large Nielsen-Lohse tied arch bridge with steel columns and cables supporting the deck. Main span of 252 m and a rise of 42 m, constructed in 1993. The caisson foundation of the bridge was located about 23 m away from the revetment.

Damage: Bridge was located in an area of liquefaction. Some soil modification had been done to this area but with only limited success. The revetment moved about 2 m in the direction of open water causing foundation movement and with the superstructure being pulled off its bearings, breaking the restrainers. Some of the cables supporting the bridge deck were also damaged. The bent of an abutment rotated with evidence of longitudinal movement of the roadway and lateral spreading of the soil (2, pg 197).

Rokko Island Bridge: Harbor Highway, Route 5 (western end)

Distance to Epicenter, **R ≈ 20 km**

Damage Severity Rating, **DSR = 3**

Structure: Lohse tied arch bridge with 217 m spans rising 36 m, with steel columns.

Damage: Bridge damage was caused by excessive substructure movements. A bearing failure on one side of this bridge racked the arch which buckled the top of the crossframing.

Shukugawa Bridge: Harbor Highway, Route 5

Distance to Epicenter, **R ≈ 20 km**

Damage Severity Rating, **DSR = 3**

Structure: A 3-span continuous steel box girder bridge. Girders supported on concrete multi-column bents and piled footings.

Damage: Widespread liquefaction and lateral spreading was evident at many locations in the general area. Both banks of the Shukugawa were subject to large soil deformations and moved toward the center of the river. Two piers were displaced with the soil and in the process dislodged the bearings under the main girders as well as the approach spans. Pier movements were on the order of 0.5 to 1 m. In addition to the bearing damage, the expansion joints were also dislodged and twisted out of alignment by larger vertical (up to 600 mm) and horizontal offsets imposed by the piers.

At one of the piers, the one m movement of the pier almost caused collapse of the approach span due to insufficient seat width at the cap. Preliminary results from the excavation behind the footing under the pier indicate that some piles failed during the lateral spreading and that replacements will be necessary around the perimeter of an expanded footing.

Kobe Bridge: Kobe side support

Distance to Epicenter, **R ≈ 20 km**

Damage Severity Rating, **DSR = 2**

Structure: The abutment had a caisson foundation which was also used as a revetment.

Damage: The revetment moved about 60 cm toward open water. This displacement was partly attributable to movement of another abutment with a fixed shoe on the Port Island side. Except adjacent to the bridge

abutment, the jetty edge revetment moved about 1.5 m toward open water and also subsided about 1 m. The backfill behind the abutment subsided about 1 m (2, pg 197).

Approach to Kobe Bridge: Jetty No. 4 of the Kobe Port

Distance to Epicenter, **R ≈ 20**

Damage Severity Rating, **DSR = 2**

Structure: The right and left piers have raft and pile foundations, respectively. The right raft foundation was supported on an artificially reclaimed rubble mound layer.

Damage: The raft foundation settled and tilted due to the liquefaction of the surrounding subsoils, followed by settlement and inclination of the pier and cross beam. This structure will be rebuilt by using a pile foundation (2, pg 196).

General Damage to Bridge Structures:

- The Rokko Liner Bridge (railway), a simply supported steel girder bridge, experienced severe damage as a result of liquefaction-induced soil movements. One of the spans dropped from the pier because the pier moved toward the sea due to large displacement of the surrounding soil mass. According to the on-ground survey which was conducted by Kobe City after the earthquake, the top of the concrete caisson of the foundation displaced about 80 cm toward the sea. It was also noted that the ground about 100 m from the sea wall also moved toward the sea about 1 m.

Distance to Epicenter, **R ≈ 20 km**

Damage Severity Rating, **DSR = 2**

- The revetment and piers with steel pipe piles were damaged on the West Jetty at the Maya Wharf. The jetty revetment moved toward the sea and footings of the elevated approach span to the Second Maya Bridge were exposed. It was therefore suggested that the steel pipe piles were subjected to lateral flow pressure of subsoils during the earthquake, that is, they became “passive piles during the earthquake.” Subsequent X-ray inspection of the steel pipe piles found that the piles experienced no damage even for the “passive piles during the earthquake,” (2, pg 197).

Distance to Epicenter, **R ≈ 20 km**

Damage Severity Rating, **DSR = 0**

1994 NORTHRIDGE EARTHQUAKE

Date of Occurrence: January 17, 1994
Magnitude: $M_W = 6.7$
Location: The epicenter was located under the north-western end of the San Fernando Valley (Northridge). The focal depth was approximately 18.4 km.
Reference: (6) and (7)

General Damage to Bridge Structures:

- At the SR14/I-5 Interchange, ground disturbance around the bases of some piers indicated lateral movements of pier and pile of as much as 200 to 250 mm (8 to 10 in) during the earthquake. No comment is made regarding the nature of these movements.
- In the river bank areas between Santa Clarita and Fillmore, Highway 23 crosses over the Santa Clara River. Near here, sand boils were observed near a bridge pier for an overcrossing under construction. Cracks induced by lateral spreading were found approximately 4.5 m (15 ft) away from the pier. The liquefaction in the river bank area caused no apparent damage to the bridge structure.

Distance to Rupture Zone, **R** \approx **37 km (20 mi)**

Damage Severity Rating, **DSR** = **0**

1994 MINDORO ISLAND, PHILIPPINES, EARTHQUAKE

Date of Occurrence: November 15, 1994
Magnitude: $M_W = 7.1$
Location: Located between the islands of Mindoro and Luzon, Republic of the Philippines. The epicenter was approximately 10 km from Calapan with rupture length of about 35 km and a focal depth of 7 to 12 km.
Reference: (8)

General Observations:

A total of 18 bridges sustained damage due to the earthquake. The damage was often limited to settlement and cracking of the approach embankments due to liquefaction and lateral spreading effects. Five multi-span bridge structures were more seriously damaged and will need partial or complete replacement.

Most existing bridges were of reinforced concrete construction with some larger spans consisting of steel trusses or steel girder construction. All bridge superstructures were observed to be simply supported, often with narrow seat widths and high, rocker-type bearings.

Most of the damage seemed to be associated with extensive liquefaction of approach embankments and under piers rather than strong ground motion shaking effects. Abutment failures were often associated with large lateral spreading effects rather than due to acceleration of the superstructure into the backwalls. Bridge damage patterns for this earthquake appear to follow the classic cases as found to occur in many less-developed, seismically active areas: loss-of-seat failures, tilting of rocker bearings, foundation failures associated with pier tilting and liquefaction, subsidence of approach fills, etc.

General Damage to Bridge Structures:

- A simply supported, reinforced concrete deck and girder bridge on Mindoro Island was damaged. It had severely rotated seat-type abutment with broken piles.

Distance to Epicenter, **R** \approx 2 km
Damage Severity Rating, **DSR** = 3

1993 ISLAND OF GUAM EARTHQUAKE

Date of Occurrence: August 8, 1993
Magnitude: $M_S = 8.1$, $M_W \approx 8.4$
Location: In the Marianas trench about 60 km south of Guam, 60 km SSW of Agana. The fault plane was estimated to be 60 km beneath the ocean floor.
Reference: (9) and (10)

General Damage to Bridge Structures:

- Soil failure in the form of slumping or spreading damaged roadways in certain locations on the island. Concrete beam bridges suffered minor cracking and slumping at abutments. Several bridges were closed for about a day due to settlement at the abutments and minor cracking in the concrete. Water mains attached to the sides of bridges failed due to differential movement at the interface of abutments.

Distance to Rupture Zone (general), **$R \approx 50$ km**
Damage Severity Rating (general), **$DSR = 1$**

1993 HOKKAIDO NANSEI-OKI, JAPAN, EARTHQUAKE

Date of Occurrence: July 12, 1993
Magnitude: $M_W = 7.8$
Location: The epicenter occurred about 160 km west of Sapporo, 60 km north of the Island Okushiri in the Sea of Japan at a depth of 27 km. The aftershock plane indicated a fault length of about 150 km and an average width of about 40 km.
Reference: (11), (12), (13) and (14)

General Observations:

Bridge performance was generally very good, with few bridges sustaining more than minor damage. Several bridges did suffer minor damage as a consequence of liquefaction-induced ground displacements. Several other bridges traversed areas of significant liquefaction effects, but were not visibly damaged. The most common disruption at bridge sites was settlement of approach fills due to compaction of embankment materials.

The most common type of bridge damage associated with liquefaction was generated by lateral displacement of abutments toward river channels. These displacements were most likely caused by lateral spread of floodplain sediments toward river channels, but may also have been caused by inward rotation of abutment walls due to compaction-induced increases in lateral forces. The abutment displacements crowded walls into bridge stringers and compressed railings and other linear features spanning the bridges.

Assabu River Bridge: Highway 227 at Azabu-cho
Distance to "Aftershock Zone," $R \approx 80$ km (from eastern edge)
Damage Severity Rating, **DSR = 1**

Structure: Six-span, two-lane, 156-m long, 8-m wide, 1970-vintage steel plate girder highway bridge. Columns are approximately 1.8 m in diameter. 1.75-m-diameter reinforced concrete bridge piers.

Damage: Lateral spreading was observed on the south bank of the bridge, which did not appear to affect the superstructure. Significant cracking was observed just above the waterline at the bridge piers founded in the river, with the northernmost in-river pier having significant spalling and broken hoop reinforcement. Lateral spreading of the ground into the river caused settlement of ground away from bridge pier (11).

General Damage to Bridge Structures:

- One of the more serious consequences of liquefaction of soils near bridge foundations was the 3° tilt of a bridge on Highway 5 in Oshamanbe. Here, a supporting caisson under the bridge had tilted 3° to the left. Evidence of sand boil deposits showed that soil liquefaction had occurred very near the pier. After construction of the bridge in 1960, it was widened by placing additional girders and decking on the west side. This widening of the bridge placed an eccentric load on the caissons. Liquefaction of soil around the caissons apparently weakened the soil sufficiently to allow the caissons to tilt in response to the earthquake forces and the static eccentric load.

Distance to Epicenter, **R ≈ 100 km**

Damage Severity Rating, **DSR = 2**

- Kamiiso-shin Bridge on Highway 228, northwest of Hokodate suffered damage as the abutment wall was displaced or rotated inward toward the river channel, causing the bridge bearings to yield and rotate toward the abutment as the girder pushed into the wall. The webs of the steel girder impacted and penetrated into the abutment wall.

Distance to Epicenter, **R ≈ 110 km**

Damage Severity Rating, **DSR = 1**

- Similar, but less damaging, displacements occurred at the Highway 229 crossing of the Assabu River north of Esaghi. The east side bearing rotated slightly due to a small amount of inward movement of the abutment. On the west side, the girder slipped through the bearing also due to the inward shift of an abutment in response liquefaction-induced ground displacements.

Distance to Epicenter, **R ≈ 80 km**

Damage Severity Rating, **DSR = 1**

- The Highway 229 bridge over the Toshibetsu River, near Kitahiyama was undamaged even though the structure is located in an area where widespread liquefaction effects developed in the floodplains beneath the bridge on both sides of the river. In the vicinity of the bridge, liquefaction-induced lateral spreads developed, with floodplain deposits shifting as much as 1 m toward the river channel. By inspecting the foundations, it was found that surrounding soil had moved relative to the bridge piers. A 0.3 m gap was found on the west side of one pier which was determined to be most likely created by oscillation of the ground about the pier, aided by oscillation of the pier and bridge. On the north side of the pier, the soil had crowded against the foundation. These soil disturbances indicate that the pier stayed in place while the surrounding soil shifted around the pier and toward the river.

Distance to Epicenter, **R ≈ 80 km**

Damage Severity Rating, **DSR = 0**

1992 ERZINCAN, TURKEY, EARTHQUAKE

Date of Occurrence: March 13, 1992
Magnitude: $M_S = 6.8$, $M_W \approx 6.7$
Location: Along the North Anatolian Fault in eastern Turkey. The epicenter was located approximately 7.7 km southeast of the city center of Erzincan. The hypocenter was located at a depth of about 25 km and the rupture occurred along 50 to 60 km of the fault.
Reference: (15) and (16)

Railway Overcrossing Bridge: Road to Kemah (southwest of Erzincan)

Distance to Rupture Zone, $R \approx 5$

Damage Severity Rating, $DSR = 2$

Structure: A 3-span railway overcrossing with a deck supported by three main girders which are simply supported on the pier bents. The middle span is 12 m long, and the 80 cm diameter piers are about 6 m tall.

Damage: The northern abutment wing wall slipped toward the bent by some 20 cm, cracking heavily. The abutment fills on both approaches settled heavily and separated from the deck. Retaining walls rotated, top towards rails. Bridge was closed when continuing deflection of the north retaining wall allowed fill settlement below the level of bridge deck.

Comments: Liquefaction was not clearly identified as the cause of damage, but at a location near the bridge site, liquefaction was noted between the road and railroad. The bridge is located in flood plain deposits approximately 5 km from the Kasrasu River.

Unlined Canal Crossing Bridge: Highway between Erzurum and Erzincan

Distance to Rupture Zone, $R \approx 5$ km

Damage Severity Rating, $DSR = 1$

Structure: Single span, simple beam bridge of low height

Damage: Settlement of piers. The piers were slightly inclined towards the south by approximately 3° and there was slight spalling at the connections between the beams and girders.

Comments: Simple beam bridges of low height were not damaged at all. Once again, liquefaction was not identified as the cause nor was there any mention of liquefaction evidence. Movements may be solely due inertial effects.

1991 COSTA RICA EARTHQUAKE

Date of Occurrence: April 22, 1991
Magnitude: $M_S = 7.5$, $M_W \approx 7.4$
Location: In the Talamanca Mountains in Costa Rica. The epicenter was located about 39.5 km SSW of the Port of Limon, at a focal depth of about 21.5 km.
Reference: (17), (18), (19) and (20)

General Observations:

Reconnaissance reports indicate that the structural aspects of the following bridges seemed to contribute to the damage. Pile lengths were probably inadequate (typically only about 19 to 20 m long) and not founded on firm and stable materials. Additionally, most of the bridges lacked redundancy. Spans were simply supported at abutments and at interior spans, so rotation of abutments or internal bents were not resisted by structural action. Span support lengths were generally inadequate at internal piers, but reasonably generous at abutments. Some bridges had rigid restrainers between spans, but no restrainers between ends of spans and abutments. Continuity of spans, and possibly integral span / abutment details, might have reduced the extent of damage, and particularly reduced the incidence of collapse.

Bridges located in the high plane (El. 1300 m), approximately 32 to 40 km from the rupture plane, revealed very little bridge damage. Bridges were primarily short single-span slab bridges on solid concrete abutments, with alluvial approach material that included large gravel and rocks rather than sands and silts.

Rio Destierro Bridge: Route 32 (75 km northwest of Limon)
Distance to Rupture Zone, **R \approx 53 km (33 mi)**
Damage Severity Rating, **DSR = 1**

Structure: A 3-span prestressed concrete I-beam bridge.

Damage: Minor abutment slumping and damage to the abutment seating due to failure of keeper-angle lateral supports.

Rio Pacuare Bridge: Route 32 (north of Limon)
Distance to Rupture Zone, **R \approx 40 km (25 mi)**
Damage Severity Rating, **DSR = 0**

Structure: A long multispan prestressed concrete girder bridge.

Damage: Undamaged.

Rio Quebrada Calderon and Rio Aguas Claras Bridges: Rt 32 (40 km from Limon)

Distance to Rupture Zone, **R ≈ 29 and 82 km (18 and 20 mi)**

Damage Severity Rating, **DSR = 1**

Structure: Both bridges were single span.

Damage: Extensive slumping of abutment fill material, but the use of settlement slabs on the approaches of both bridges enabled them to remain serviceable.

Rio Chirripo Bridge: Route 32 (between San Jose and Limon)

Distance to Rupture Zone, **R ≈ 23 km (14 mi)**

Damage Severity Rating, **DSR = 3**

Structure: Six-span continuous steel girder bridge with a short, 16 meter, simply supported span at the end.

Damage: Short end span lost to liquefaction. The slab pier support at the end of the span rotated inwards, together with probable abutment movement.

Rio Buffalo Bridge: Route 32 (10 km from Limon)

Distance to Rupture Zone, **R ≈ 21 km (13 mi)**

Severity Rating, **DSR = 3**

Structure: A 3-span prestressed concrete beam and slab bridge.

Damage: Abutment material failure with severe rotation of the abutments and slumping of the bank material that exposed piles.

Rio Banano Bridge: Route 36 (south of Limon)

Distance to Rupture Zone, **R ≈ 27 km (17 mi)**

Damage Severity Rating, **DSR = 3**

Structure: Single lane bridge consisting of three 22 m spans of twin prestressed concrete I-beams with a shorter span at the north end. Piles are 36 cm² precast concrete. Front piles are driven at a batter of 1:5.

Damage: Extensive signs of liquefaction were present. Soil movement caused about 9° rotation of the south abutment resulting in a movement of the pile tops toward the river of about 66 cm. Front piles suffered flexural as well as shear failures. Vertical piles at rear showed less damage.

Comments: Near the bridge, a several hundred foot wide flood plain consisting of sand and gravels liquefied and spread laterally towards the river on shallow slopes. The approach fills behind the southern embankment slumped, with some of the materials slipping towards the river through pile bents. The log of a boring drilled at the south abutment shows that the surficial sands and gravels are relatively thin and, in general, the piles are supported by silty and clayey materials.

Rio Viscaya Bridge: Route 36 (south of Limon)

Distance to Rupture Zone, **R ≈ 27 km (17 mi)**

Damage Severity Rating, **DSR = 3**

Structure: A 3-span prestressed concrete I-beam bridge. Each span is simply supported on the abutments and/or interior piers.

Damage: Two spans lost due to severe abutment rotation, pile distress, and collapse of one interior support. A second interior support settled vertically about 1 m. The south abutment rotated 8° and was pushed towards the center of the river. Hinge restrainers between the spans pulled out of the span end diaphragms. Total collapse of this structure might have been averted by a less articulated design.

Comments: The bridge was founded in soft sands, effectively on the shoreline, and collapsed due to loss of support and ground deformations resulting from soil liquefaction. The log of a boring drilled near the north abutment shows that the entire length of piles is supported in sands and silty sands. Liquefaction soils in approach fills caused lateral spreading and bearing capacity failure. The north roadway approach fill settled approximately 120 cm. North and south abutment rotation was caused by movement of liquefied soils.

Rio Bananito Bridge: Route 36 (south of Limon)

Distance to Rupture Zone, **R ≈ 27 km (17 mi)**

Damage Severity Rating, **DSR = 3**

Structure: A two span skewed prestressed concrete I-beam bridge. The bridge abutment and central slab pier were skewed at 30°.

Damage: Both spans were lost off the central pier, with the spans being thrown off in the direction of the skew. Both abutments rotated towards the river at

the base. The southern abutment rotated about 15° due to lateral flow of the ground towards the river.

Comments: The road runs on a sand bar in the north and on a marsh in the south. Many fissures parallel to the river were observed along the river bank and the approach roadway slumped.

Estero Negro Bridge: Route 36 (south of Limon)

Distance to Rupture Zone, **R ≈ 27 km (17 mi)**

Damage Severity Rating, **DSR = 3**

Structure: Two span prestressed concrete I-beam bridge.

Damage: One span fell down. The lateral flow of the ground at the right river bank pushed the abutment and the remaining span, which resulted in the falling down of the missing span.

Comments: There was another bridge crossing a small creek about 3 km south from the Rio Estero Negro bridge. The approach roadway subsided but the bridge was not damaged.

Rio Estrella Bridge: Route 36 (south of Limon)

Distance to Rupture Zone, **R ≈ 26 km (16 mi)**

Damage Severity Rating, **DSR = 1**

Structure: Bridge consisted of two 75 m steel truss spans, with a 25 m prestressed concrete I-girder span at the northern end.

Damage: Both truss spans fell off their supports. The south span fell off the south abutment, and collapsed at the central abutment by fracture of the two bottom cords immediately adjacent to the central slab pier. The end diagonal buckled and the span dropped. The northern span pulled off the central support but was still supported at the northern end.

Comments: The roadway approach to the south abutment of the bridge, as well as the banana plantations on both sides of the road, were dissected by several large and many small fissures indicative of liquefaction at depth and lateral spreading of surface flood-plain deposits toward the river channel. Lateral displacements were as large as 1 to 3 m based on open widths of fissures observed in the roadway and adjacent banana fields. The soil supporting the roadway at the south abutment compacted during the earthquake causing the approaching roadway to settle about 1.5 m. Roadway settlement near the north abutment was about 0.2 m. Only a

few longitudinal cracks developed in the pavement and approach fill; no open fissures were found in natural ground within several tens of meters of the north abutment.

Despite signs of large soil movements at the southern abutment, there were no signs of permanent deformation or rotation. An investigation was made where pertinent points on each abutment and pier were surveyed to determine post-earthquake distances between structural elements for comparison with distances noted on the bridge plans. The comparisons indicate very little displacement of the piers and abutments during the earthquake. The differences between plan and measured distances fall within the range of expected survey and construction error and indicate that no substantial permanent displacement occurred between these elements. **The foundation for this abutment apparently was sufficiently strong to resist the lateral soil movement and hold the abutment in place.**

1990 LUZON, PHILIPPINES, EARTHQUAKE

Date of Occurrence: July 16, 1990
Magnitude: $M_S = 7.8$, $M_W \approx 7.9$
Location: Located in the Island of Luzon, Republic of the Philippines, about 200 km north of Manila. Epicenter was northeast of Cabanatuan, in the town of Bingabon. Surface faulting was observed for 110 km and may have extended another 100 km to the north. The focal depth was about 36 km.
Reference: (21), (22), (23), (24) and (25)

Magsaysay Bridge: Dagupan, Perez Blvd (downtown, across the Pantel River)
Distance to Rupture Zone, **$R \approx 60$ km**
Damage Severity Rating, **DSR = 3**

Structure: Seven-span reinforced concrete bridge supported by six piers and two abutments. Bridge is 144 m long comprised of eight simply supported reinforced concrete girders resting on piers supported by concrete piles about 10 m in length.

Damage: Piers settled and/or tipped over. The ends of two spans that the bridge supported dropped, into the water. The first and second piers from the right bank moved toward the river channel due to lateral spread of the river bank and the third pier sank about 2 m due to loss of bearing capacity of the liquefied riverbed deposit.

Comments: Liquefaction caused buildings at both ends of the bridge to settle. A bridge approximately 800 m to the west was not damaged.

Carmen (Sison) Bridge: Route 3 (between Santo Tomas and San Manual)
Distance to Rupture Zone, **$R \approx 60$ km**
Damage Severity Rating, **DSR = 3**

Structure: The bridge is about 1.6 km long and consists of 13 steel-truss spans supported on concrete piers. The type of foundation used for the piers is not known.

Damage: Six of the spans collapsed. The primary cause of failure was the movement of piers, which was caused by liquefaction, loss of bearing capacity, and lateral spreading.

Comments: About one-third of this bridge crosses the waterway; the remaining portion runs over the adjacent flood plain. The bridge is underlain by

quaternary alluvial, lacustrine, beach, and residual deposits. Numerous large sand boils were seen in the area.

Cayanga Bridge: Coastal road south of Agoo

Distance to Rupture Zone, **R ≈ 65 km**

Damage Severity Rating, **DSR = 1**

Structure: Long, “modern” bridge with concrete spans and piers.

Damage: The approach to the south abutment had settled, and there was extensive cracking and subsidence in the soil adjacent to the abutment. Lateral spreading caused slight shifting in a support column and an offset in a bridge support pad.

Comments: Bridge was relatively undamaged, although there was significant lateral spreading, and settlement of the soils and road bed adjacent to the south abutment.

1989 LOMA PRIETA EARTHQUAKE

Date of Occurrence: October 17, 1989
Magnitude: $M_W = 6.9$, $M_S = 7.1$
Location: The epicenter was located 16 km northeast of Santa Cruz and approximately 30 km south of San Jose. The depth was approximately 18 km below the surface of the Earth.
Reference: (26)

General Observations:

Minor liquefaction, as evidenced by small sand boils, occurred beneath several elevated sections of the highway “distribution structure” immediately inland of the Bay Bridge approach fill. Several of these boils were adjacent to one of the elevated support bents in this area. The minor liquefaction does not appear to have resulted in any significant damage to the distribution structure.

Within a few hundred yards of the destroyed Marine Research Facility, located on a sandy peninsula between the Pacific Ocean and the old trace of the Salinas River, an approach fill to a timber pile supported bridge across the old Salinas River was found to have slumped approximately 1 to 1.5 m, severing water and/or sewer pipe lines running across the bridge.

General Damage to Bridge Structures:

- Soquel Avenue Bridge in Santa Cruz (42).
Distance to Rupture Plane, $R \approx 22$ km (12 mi)
Damage Severity Rating, $DSR = 1$
- Broadway Avenue Bridge in Santa Cruz (42).
Distance to Rupture Plane, $R \approx 22$ km (12 mi)
Damage Severity Rating, $DSR = 1$
- Riverside Avenue Bridge in Santa Cruz (42).
Distance to Rupture Plane, $R \approx 22$ km (12 mi)
Damage Severity Rating, $DSR = 1$
- Highway 1 Bridge at Moss Landing (42).
Distance to Rupture Plane, $R \approx 22$ km (12 mi)
Damage Severity Rating, $DSR = 1$

- Highway 1 Bridge at Pajaro River (42).
Distance to Rupture Plane, **$R \approx 29$ km (15.5 mi)**
Damage Severity Rating, **DSR = 0**
 - Small wooden bridge at Moss Landing (42).
Distance to Rupture Plane, **$R \approx 22$ km (12 mi)**
Damage Severity Rating, **DSR = 1**
 - Corralitos Creek Bridge (42).
Distance to Rupture Plane, **$R \approx 11$ km (6 mi)**
Damage Severity Rating, **DSR = 1**
 - County Bridge near Salinas River (42).
Distance to Rupture Plane, **$R \approx 27$ km (14.5 mi)**
Damage Severity Rating, **DSR = 0**
-

1983 NIHONKAI-CHUBA EARTHQUAKE

Date of Occurrence: May 26, 1983
Magnitude: $M = 7.7$ (Richter), $M_w = ?$
Location: Located in the coastal area of central Japan Sea, Akita and Aomori Prefectures
Reference: (40)

General Damage to Bridge Structures:

- Excessive settlements of an approaching bank to Gomyoko Bridge in Hachirogat lagoon, Akita Prefecture were observed. It was noted that those settlements were caused by liquefaction of supporting sand layers. Gomyoko Bridge had very minor damage to reinforced concrete piles, despite the serious settlements of the approach road embankments.

Distance to Epicenter, $R \approx 125$ km
Damage Severity Rating, $DSR = 0$

- Jusanko Bridge in the northern part of Aomori Prefecture had settlements on the order of 50 cm observed in the neighboring ground surfaces due to sand liquefaction. Although serious settlements and cracks occurred at ground surfaces, the bridge did not receive serious structural damage, except settlement of one pier (about 10 cm). Approach banks to both abutments settled considerably (about 1 m).

Distance to Epicenter, $R \approx 160$ km
Damage Severity Rating, $DSR = 1$

1980 EL-ASNAM, ALGERIA, EARTHQUAKE

Date of Occurrence: October 10, 1980
Magnitude: $M_S = 7.3$, $M = 7.2$ (Richter), $M_W \approx 7.2$
Location: The epicenter was located approximately 10 km east of El-Asnam at a focal depth of about 10 km.
Reference: (27)

General Observations:

Most bridge abutments settled during the earthquake, thereby damaging bridge approaches. The differential settlement was jointly due to lurching, liquefaction, and uneven compaction.

Cheliff River Bridge: 15 km NE of El-Asnam and about 5 km SW of Beni Rached
Distance to Rupture Zone, $R \approx 5$ to 10 km
Damage Severity Rating, **DSR = 1**

Structure: Two-lane modern prestressed concrete bridge continuous over five spans. Intermediate spans are supported on twin piers, the lower ends of which are protected from scour by a steel caisson lining.

Damage: Except for some cracking of concrete at the foundation in the steel caisson, there was no evidence of structural damage to the spans, piers, or foundation. There was also no evidence of pier settlement. The only faulty detailing was at each end, where bearing beams that transferred the bridge load to the wing walls had moved. These bearing beams were keyed into the abutment approach structure but were not tied back; so in the case of the southern abutment, which had undergone a significant rigid body rotation, its bearing beam was almost lost. Relative movement to 1 m horizontally and 0.30 m vertically occurred between the approach and the deck.

Comments: Along the river in the neighborhood of the bridge, considerable land movement and soil liquefaction were observed.

1979 IMPERIAL VALLEY, CALIFORNIA EARTHQUAKE

Date of Occurrence: October 15, 1979
Magnitude: $M_w = 6.5$
Location: The epicenter was located 3 km south of the U.S. / Mexico border approximately 10 km east of Mexicali, Mexico. The focal depth was about 9.7 km and surface faulting occurred along the Imperial fault (30.5 km), the Brawley fault (13.1 km) and the Rico fault.
Reference: (28), (29), (30) and (31)

New River Highway Bridges 58-05 R/L: Highway 86 (3 km west of Brawley)
Epicentral Distance of 41 km, Distance to Rupture Zone, **$R \approx 7$ to 10 km**
Damage Severity Rating, **DSR = 1**

Structures: Each bridge is a 60 m long span of reinforced concrete slabs supported on nine sets of six piles. The piles are Raymond step-tapered shells below groundline with octagonal cast-in-place PCC extensions to the caps. The minimum depth of embedment of the piles was about 9 m. The bridges were built in 1953.

Damage: Damage was relatively slight. Counterclockwise rotation of the superstructure in a horizontal plane cracked and tilted the support piles and wingwalls. The top of the piles at Bent 2 had open horizontal cracks on their northern faces and spalls on their southern. Similarly, the top of the piles at Bent 8 had open horizontal cracks on their southern faces and spalls on their northern faces. The piles at Bents 2 and 8 were tilted 3.2° in the direction bridge rotation. The relative rotation of the bridges and the pattern of concrete damage at the tops of the piles was most likely caused by southwestern movement of the foundation soils on the east bank of the river and northeastward movement of the foundation soils on the west bank of the river.

Comments: Ground cracks and soil slumping were observed on both the east and west river banks. Soil slumped toward the river at least 100 mm. Conical depressions had formed on the downslope side of the base of the piles, and soil was compressed around the upslope faces. Settlement around the piles was measured as 40 mm. No sand boils were seen beneath the bridges.

1978 MIYAGI-KEN-OKI, JAPAN, EARTHQUAKE

Date of Occurrence: June 12, 1978
Magnitude: $M_S = 7.4$, $M_W \approx 7.3$
Location: The epicenter is located offshore Japan, approximately 115 km east of Sendai, from a focal depth of about 60 km.
Reference: (32), (33) and (40)

Yuriage Bridge: Located outside Sendai (1.2 km from the mouth of the Noatori River)
Distance to Epicenter, **$R \approx 107$ km**
Damage Severity Rating, **DSR = 1**

Structure: A 10-span bridge constructed in 1962. Seven prestressed-concrete T-girders, each 45 m long, and three main spans. The spans are twin-cell, segmentally constructed, post-tensioned concrete box girders. The center span which is 90 m long, has a 60 m span at either end.

Damage: The bridge was open to only one lane of traffic because of heavy column damage. No damage was reported to the three-span box structure. Light girder impacting with the abutment and pronounced shear cracking of the exterior girder at the bearing was evident. Pier 1, founded on a caisson 19 m deep and 2 m by 4 m in plan, suffered heavy shear cracking. The pier cap was reported to have settled 5 cm uniformly.

Comments: Liquefaction was evident in the flood plain below the bridge.

General Damage to Bridges Structures:

- Abukuma Bridge, located on National Highway No. 6, sustained heavy cracks to several pier columns. A sand boil was observed next to one the bridge piers.

Distance to Epicenter, **$R \approx 112$ km**
Damage Severity Rating, **DSR = 2**

1976 MINDANAO, PHILIPPINES, EARTHQUAKE

Date of Occurrence: August 17, 1976
Magnitude: $M_S = 7.9$, $M_W \approx 7.9$
Location: The epicenter was located offshore in the Moro Gulf approximately 110 km south of Cotabato City and about 12 km west of Cadiz Point.
Reference: (34)

General Damage to Bridge Structures:

Soil movements and failures were found at two bridges in Cotabato City. Abutment soil cracks were exhibited at the Quirino and Tamontaka Bridges. Notable ground cracking occurred to the west of the Quirino Bridge on both sides of the Rio Grande. Some of these ground cracks were 25 cm wide and 1.8 m deep, with as much as 25 cm of settlement on the river side.

- The Quirino Bridge is a four span structural steel bridge. Each span of this bridge over the Rio Grande de Mindanao River is 40 m long. The second span from the south end collapsed into the river during the earthquake. The northerly pier appeared to be leaning to the north. Two blocks west of the Quirino Bridge, observations were made of the ground sloughing in on both sides, toward the center of the river.

Distance to Epicenter, **$R \approx 110$ km**
Damage Severity Rating, **DSR = 1**

- The Tamontaka Bridge is located approximately 6 km SSW of Central Cotabato City. Spanning some 230 m across the Tamontaka River, the bridge is made up of six spans resting on pile supported piers. The 180 cm deep box girder sections, as well as piers and piles are reinforced concrete. Most of the damage to this bridge appears to be related to inertial effects. One exception is the movement of the abutments. Soft, swampy land surrounds the bridge. Displacement was visible between the roadway and its apron, north of the bridge. Displacements on the north end of the bridge on the order of 46 cm, sheared a 26 cm cast iron water supply pipe.

Distance to Epicenter, **$R \approx 104$ km**
Damage Severity Rating, **DSR = 1**

1976 TANGSHAN, CHINA, EARTHQUAKE

Date of Occurrence: July 28, 1976
Magnitude: $M_S = 7.8$, $M_W \approx 7.8$
Location: Located outside Tangshen city with a focal depth of 12 to 16 km. The maximum epicentral distance, $R_{\max} \approx 180$ km, was calculated using the empirical equation: $\log R_{\max} = 0.77M - 3.6$.
Reference: (35)

General Observations:

Severe soil liquefaction occurred especially within young alluvial deposits of the Holocene period or within abandoned river channels. It was noted that highway bridges whose pile foundations were placed in liquefaction susceptible deposits but not sufficiently embedded in firm layers were severely damaged.

Several kinds of damage to bridges were induced during this earthquake. It is reported that several bridges were damaged due to soil liquefaction. There were no cases of extensive settlements of bridge foundations even when liquefaction occurred in the adjacent river beds. It is considered that this was due to the fact that the foundation piles were deep enough, extending into firm soil layers and also that the soil liquefaction occurred in shallow deposits at these bridge sites. The damage to bridges was mainly due to the horizontal movement or the sliding of soil masses adjacent to the bridge foundations and the river dikes toward the river centers.

Shen Li Bridge: Tangshen City (over the Dou River)

Distance to Epicenter, $R \approx 180$ km

Damage Severity Rating, $DSR = 3$

Structure: Completed in 1966. Five simple-supported girders of reinforced concrete with a total length of 55 m. Each pier consisted of three pile bents having a diameter of 1 m and a length of 24.5 m with the portion of a length of 18 m being embedded. The 8 m high abutments were of gravity-type consisting of stones.

Damage: The ground adjacent to the bridge moved toward the center of the Dou River and in turn shifted horizontally the abutment of the bridge toward the center of the river, resulting in the dislodging of the superstructure. The horizontal movement on the right side of the bank was 1.15 m and for the left side of the bank, 2.45 m.

Comments: It was reported that in the river bed adjacent to the bridge there was a liquefaction-susceptible sandy layer existing from the river bed surface

to a depth of around 10 m. Several slumps parallel to the river were found on the ground within 10 to 15 m apart from the river banks.

Daodi Bridge: South of Tangshan City

Distance to Epicenter, **$R \approx 180$ km**

Damage Severity Rating, **DSR = 3**

Structure: Total length of 50.4 m.

Damage: Total length was reduced by as much as 3.2 m due to slides of the river dikes toward the river center. The abutment was shifted horizontally by the horizontal movement of the river dike. The piers were tilted probably due to the horizontal movement of the river bed toward the river center.

Shahe Bridge: Located near Lei Zhuang in Luan County

Distance to Epicenter, **$R \approx 180$ km**

Damage Severity Rating, **DSR = 3**

Structure: Total length of 216.4 m.

Damage: Piers inclined and among them one crashed down and the girders supported by that pier fell down. The maximum relative displacement at the level of the top of the pier between girders and piers was 1.05 m in the direction of bridge axis and 0.4 m in the direction perpendicular to the bridge axis.

Comments: Sand boils and spouted water were observed on the ground surface of the flood plain adjacent to the piers. A spread of river embankment was also induced.

Ninghe Bridge: North of Hangu

Distance to Epicenter, **$R \approx 180$ km**

Damage Severity Rating, **DSR = 3**

Structure: Total length of 170 m.

Damage: Total length was decreased by 1.8 m during the earthquake. The river banks slid toward the river center. The river bank sank and cracks appeared. One reinforced concrete arch frame and one girder fell down.

1975 HAICHENG, CHINA, EARTHQUAKE

Date of Occurrence: February 4, 1975
Magnitude: $M_S = 7.3$, $M_W \approx 7.2$
Location: Located in the northeastern region of China with a focal depth of approximately 12 km. The maximum epicentral distance, $R_{\max} \approx 110$ km, was calculated using the empirical equation:
 $\log R_{\max} = 0.77M - 3.6$.
Reference: (35)

General Observations:

Severe soil liquefaction occurred especially within young alluvial deposits of the Holocene period or within abandoned river channels. It was noted that highway bridges whose pile foundations were placed in liquefaction susceptible deposits but not sufficiently embedded in firm layers were severely damaged.

Liao River Bridge: Located near Tian Zhuang Tai
Distance to Epicenter, $R \approx 110$ km
Damage Severity Rating, **DSR = 3**

Structure: At the time of the earthquake, part of the bridge had not been completed.

Damage: The horizontal movement of soil masses induced the horizontal movement and tilting of piers toward the river center. One pier moved horizontally 4.35 m toward the river center. The hyperbola frame of one span fell down due to the increase in the span by 0.67 m.

Comments: The river banks slumped due to soil liquefaction in the area adjacent to the bridge and a lateral spread was also generated by soil liquefaction in the flood plain between the river banks. The ground adjacent to the piers located in the flood plain moved toward the river center. Widely spread sand boils erupted on both sides of each river bank and on the flood plain between the river banks.

Panshan Highway Bridge: Located near Panshan
Distance to Epicenter, $R \approx 110$ km
Damage Severity Rating, **DSR = 3**

Structure: Reinforced concrete superstructure with 14 spans. Each of two abutments and 13 piers supported by four reinforced concrete piles with a diameter of approximately 1 m and a length of approximately 30 m.

Damage: One pier (No. 7) sank 15 cm. Other piers inclined and cracks were induced in these piers. During a major aftershock ($M_S = 5$), pier No. 7 sank again and four superstructure spans fell. Also during the aftershock, the tops of some piers inclined to the river bank due to the ground movement toward the river center.

1968 EBINO EARTHQUAKE

Date of Occurrence: February 21, 1968
Magnitude: $M = 6.1$ (Richter), $M_w \approx 6.1$
Location: Ebino, Nishimoro-kata County, southern part of Kyushu Island, with a very shallow hypocenter
Reference: (41)

Ikejima Bridge: Ebino municipal road across the Ikejima River
Distance to Epicenter, **$R \approx 10$ km**
Damage Severity Rating, **$DSR = 1$**

Structure: Abutments and two piers are of solid-slab-type reinforced concrete structures with spread footings and wooden pile foundations. The superstructure is of 3-span steel H-shaped simple girders.

Damage: A pier on the left bank settled about 25 cm. Evidence of liquefaction was noted in the general area.

1964 ALASKA EARTHQUAKE

Date of Occurrence: March 27, 1964
Magnitude: $M_w = 9.2$
Location: The epicenter was located in the Chugach Mountains near the northern end of Prince Williams Sound about 130 km east-southeast of Anchorage. The depth to hypocenter was approximated to be 20 to 50 km.
Reference: (20), (28), (36) and (37)

General Observations:

A wealth of information is available on these bridges and the soils they were founded on. Foundation displacements for over 160 bridges were classified with varying degrees of severity. Approximate distances of the damage locations from the zone of major energy release range from 80 to 150 km (see table below). The proximity of damage locations to the energy-release zone is therefore not likely to be a significant factor in determining the relative damage at the various locations or in adjacent areas. Variations in bridge behavior are more likely to be due to differences in type of superstructure, type of foundation, foundation-soil conditions, and local topography.

Table A.2: Estimated Distances from Zone of Major Energy Release to Bridge Damage Locations

GENERAL LOCATION	APPROXIMATE DISTANCE FROM ZONE OF MAJOR ENERGY RELEASE
Resurrection River	111 km (60 miles)
Snow River	111 km (60 miles)
Kenai River (Sterling Highway)	148 km (80 miles)
Turnagain Arm (Portage Area)	93 km (50 miles)
Scott Glacier Streams	93 km (50 miles)
Sheridan Glacier Streams	102 km (55 miles)
Lower Copper River	130 km (70 miles)

Instead of looking at each specific bridge and its associated damage, some of the insights that were gained from the examination of such a large bridge sampling are presented:

- No cases of evident foundation displacement were reported for bridges known to be founded wholly on bedrock.
- The greatest concentrations of bridges that sustained severe foundation movements were founded on piling driven through saturated sands and silts of low-to-medium relative density ($N < 20$).

- Bridges founded on piles that were driven through loose to medium-dense sands and silts into denser sands and silts fared better than those founded on piles that were embedded in loose to medium-dense sand and silt without reaching denser strata. The mode of failure may have been different in these two support conditions, but severe foundation displacements occurred in both.
 - Bridge foundations that were founded in gravels and gravelly sands (regardless of N values), rather than in sands and silts, behaved relatively well.
 - Severe foundation displacements in sands and silts had foundations ranging from light flexible all-timber bents through steel-rail and concrete bents to heavy reinforced-concrete piers with four-way-battered concrete-filled steel-tube piles extending to a total depth of about 30.4 m (100 ft).
 - No failures of bridges founded in cohesive soils had been reported along the highways investigated.
 - Bridge-foundation damage included horizontal movement of abutment foundations toward the channels, spreading and settlement of abutment fills, horizontal displacement and tilting of piers, severe differential settlement of abutments and piers, and failure of foundation members.
 - The severity of damage to bridge foundations was dependent to a great extent on the foundation-support conditions.
 - The greatest concentrations of severe damage occurred in regions characterized by thick deposits of saturated cohesionless soils. Ample evidence exists of liquefaction of these materials during the earthquake.
 - Bridges founded in saturated sands and silts sustained severe displacement of pile-supported foundations even where the average penetration resistance of the upper 9 m (30 ft) of the soil was as high as 25 blows/ft. The degree of damage sustained by these bridges did not appear to be greatly influenced by an increase in density of the foundation soil at the pile tips and below.
-

1964 NIIGATA, JAPAN, EARTHQUAKE

Date of Occurrence: June 16, 1964
Magnitude: $M_S = 7.5$, $M_W \approx 7.3$
Location: The epicenter was near Awa Island in the Japan Sea, 22 km off the coast of Japan. The focus of the earthquake was about 40 km deep.
Reference: (22)

General Observations:

Permanent ground displacements resulting from liquefaction in Niigata City were quite large. Horizontal displacement measurements were made using aerial photographs and are provided on pages 3.11 to 3.15 (22). **It is notable that the horizontal displacements in the vicinity of the Bandai, Yachiyo, and Showa Bridge abutments were reduced because of the resistance of the structures to ground displacements.**

Soil data, including cross sections, blow counts, and estimated liquefied layer is also available for the following bridges in the reference above. Generally, liquefaction was estimated to have occurred in the riverbed as well as in the ground on both banks.

Yachiyo Bridge: Niigata City
Distance to Epicenter, **$R \approx 55$ km**
Damage Severity Rating, **DSR = 3**

Structure: Foundations of the abutments and piers had been constructed on reinforced concrete piles with a diameter of 300 mm and a length of about 10 m.

Damage: Piles extracted and examined after the earthquake showed that the piles were severely destroyed at a depth of about 8 m from the top of the pile, and horizontal cracks, which could have been caused by the large bending moments were found through the piles. The permanent ground displacement on both banks were 4 to 6 m toward the river. The reason for pier failures can be conjectured as follows: the foundation of the piers were pushed toward the river due to large ground displacements while displacements at the top of the piers were restrained because of the resistance of the girders. This caused a large stress concentration in the center of the pier.

Showa Bridge: Niigata City
Distance to Epicenter, **$R \approx 55$ km**
Damage Severity Rating, **DSR = 3**

Structure: Modern bridge with 12 simply supported steel girders. Piers were constructed by driving steel pipe piles, which had considerable flexibility in the direction of the bridge longitudinal axis.

Damage: Five girders fell into the water. Permanent ground displacement on the left bank reached several meters, substantially deforming the foundation piles and causing the girders to fall.

1948 FUKUI, JAPAN, EARTHQUAKE

Date of Occurrence: June 28, 1948
Magnitude: $M_S = 7.1$, $M_W \approx 6.9$
Location: The epicenter was located below the eastern part of the Fukui Plain, about 10 km northeast of Fukui City. The focal depth was approximately 30 km.
Reference: (22) and (41)

Nagaya Bridge: Tajima River Area
Distance to Epicenter, **$R \approx 2$ km**
Damage Severity Rating, **DSR = 3**

Structure: Eight spans of reinforced-concrete I-beams with a total length over 58.5 m, supported on concrete piers.

Damage: Three piers sank to ground level due to liquefaction and the beams fell to the ground.

Itagaki Bridge: Hashidate-Fukui Route, across the Ashiba River
Distance to Epicenter, **$R \approx 10$ km**
Damage Severity Rating, **DSR = 3**

Structure: Gravity-type reinforced concrete abutments with twelve reinforced concrete rigid frame piers and caisson foundations. The superstructure consisted of 13-spans of reinforced concrete T-shaped girders.

Damage: Several of the piers tilted 1 to 12°. Eight spans fell into the river due to the tilting of the piers. Both abutments had heavy cracks on the parapet walls and the wing masonry.

Shioya Bridge: Near the mouth of the Daishoji River
Distance to Epicenter, **$R \approx 15$ km**
Damage Severity Rating, **DSR = 2**

Structure: Concrete abutments and seven reinforced concrete rigid frame piers. The superstructure consisted of 8-span I-shaped steel girders.

Damage: Abutments tilted slightly. Every pier tilted toward the left bank and settled. The maximum settlement was 25 cm at the second pier from the left bank.

Nagaune Bridge: Tajima River Area

Distance to Epicenter, **R ≈ 4 km**

Damage Severity Rating, **DSR = 3**

Structure: Eight spans of wooden beams supported upon timber piers with concrete foundations and a total length of 72.2 m.

Damage: Several piers sank due to loss of bearing capacity on the foundation soils as a result of liquefaction. Two piers in particular sank almost to ground level.

Comments: Both the Nagaya and Nagaune Bridges crossed the Tajima River and its tributary, respectively. It was reported that numerous sand and water boils were observed during the earthquake.

Nakatzuno Bridge: Main Channel Area of Kuzurya River

Distance to Epicenter, **R ≈ 8 km**

Damage Severity Rating, **DSR = 3**

Structure: The bridge consisted of 14 spans of I-shaped steel girders with a total length of 259 m. The piers were reinforced concrete columns on open caisson foundations.

Damage: The piers sank, tilted substantially, and collapsed, and the simply-supported girders fell. It was reported that damage to the collapsed girders was comparatively light in spite of the extensive damage to the piers.

1923 KANTO, JAPAN, EARTHQUAKE

Date of Occurrence: September 1, 1923
Magnitude: $M_S = 7.1$, $M_W = 6.9$
Location: The epicenter was in the Sagami Bay
Reference: (22) and (41)

Banyu Bridge: National Route 1, Chigasaki City (over Sagami River)
Distance to Rupture Zone, **$R \approx 50$ km**
Damage Severity Rating, **DSR = 3**

Structure: Under construction. No superstructure. Open caissons and abutments.

Damage: Open caissons leaned, rose buoyantly, and were displaced. Abutments on both banks tilted toward the river. The inclination of the abutments was about 4° and 12° for the left and right banks, respectively. The damage to the bridge indicates that ground displacement occurred in a direction towards the Sagami River in addition to the displacement towards Okawa Creek.

Comments: This area is located on the left bank of the lower reaches of the Sagami River. The geomorphological features of the Nakajima area are characterized by abandoned braided channels and abandoned channel bars. These channels and bars are covered with alluvial fan deposits. Liquefaction was very prevalent in this area (110 documented cases) with numerous large ground cracks and flooding due to the water “spurting” from the ground.

Arakawa Canal Bridge: Furu-Sumida Creek Area in Tokyo
Distance to Rupture Zone, **$R \approx 80$ km**
Damage Severity Rating, **DSR = 3**

Structure: Undetermined

Damage: The abutments settled about 0.9 m on the right bank and 1.2 m on the left bank. A pier on the west bank side was displaced in the downstream direction. The movement of the pier might be a result of the movements in the direction of the Furu-Sumida Creek.

Comments: This area is generally a deltaic zone transitioned to a natural levee zone of the Kanto Plain.

Tsurono-bashi Bridge: Bandaicho-Horaicho Road in Yokohama

Distance to Rupture Zone, **R ≈ 40 km**

Damage Severity Rating, **DSR = 2**

Structure: This bridge, completed in 1914, had brick masonry abutments with concrete foundations. Each of two piers were made of four spiral single-row cast iron pipe piles with some bracing. The superstructure consisted of 3-span simple steel plate girders.

Damage: Both abutments moved and tilted toward the center of the river, and two piers tilted considerably toward the left bank. The superstructure moved largely toward the left bank.

Toyokuni Bridge: Located between Horai-cho and Masago-cho, over the Oala River

Distance to Rupture Zone, **R ≈ 40 km**

Damage Severity Rating, **DSR = 3**

Structure: Three span, simple steel pony trusses reconstructed in 1897. Abutments and two piers were made of masonry structures with concrete fill inside.

Damage: Considerable substructure movement and one end of a truss fell into the river. Both abutments moved toward the center of the river, and tilted in the direction of their backfill. Two piers tilted considerably toward the center of the river, with an angle of inclination of over 8° at the northern pier and 2° at the southern pier.

1906 SAN FRANCISCO EARTHQUAKE

Date of Occurrence: April 18, 1906
Magnitude: $M_w = 7.9$
Location: The rupture was along 435 km (270 mi) of the San Andreas Fault. The largest displacement being 6.4 m (21 ft) approximately 48 km (30 mi) northwest of San Francisco.
Reference: (20), (38) and (39)

Salinas River Bridge: Highway Bridge (south of Salinas, CA)
Distance to Rupture Zone, **$R \approx 29 \text{ km (16 mi)}$**
Damage Severity Rating, **$DSR = 3$**

Structure: A large trussed structure in two spans and plank deck. The south pier consisted of 26 piles and was incased in planking.

Damage: 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 (20). Additional information can be found on page 292, (38) and page 13, (39).

General Damage to Bridge Structures:

- On the east bank of the main Eal River, to the east of Laytonville, the ground was cracked for a distance of 274 m (300 yd), the trend of the crack following the course of the river. The crack was merely local in the alluvial bank of the stream, perhaps 91.5 m (100 yd) from the water. A long bridge crossing the stream at this place showed no damage (38, pg 170; 39, pg 165).

Distance to San Andreas Fault, **$R \approx 57 \text{ km (31 mi)}$**
Damage Severity Rating, **$DSR = 0$**

- A railroad bridge across a lagoon in Cleone, Mendocino County, sank 1 m (3 ft) in some places, and was thrown out of line laterally, all the piling supporting the bridge were listed to the south (38, pg 172; 39, pg 165).

Distance to San Andreas Fault, **$R \approx 5.5 \text{ km (3 mi)}$**
Damage Severity Rating, **$DSR = 3$**

- In Mendocino, Mendocino County, the bridge over the Big River was severely damaged. A short span in the long approach on the north side entirely collapsed. The fall of the span was due to the shifting north of piles on the north side of the river, thus allowing one end to drop (38, pg 175).

Distance to San Andreas Fault, **R ≈ 5.5 km (3 mi)**
 Damage Severity Rating, **DSR = 3**

- An old bridge in Alexander Valley, east of Layton Springs, was wrecked, “the trestle-work art going down.” There was evidence of liquefaction in the general vicinity (38, pg 184; 39, pg 160).

Distance to San Andreas Fault, **R ≈ 29 km (16 mi)**
 Damage Severity Rating, **DSR = 3**

- It was noted that the “fills” in Tomales Bay generally sank from 0.6 to 2.5 m (2 to 8 ft). In a couple instances the pile-supported bridge in the middle of the fill remained at grade. Just above Hamlet a trestle-work which had been filled in settled, leaving the trestle-work some 0.6 m (2 ft) above. The bottom of the bay in these arms is usually sand (38, pg 197; 39, pg 152). Indications are of little damage to trestles.

Distance to San Andreas Fault, **R ≈ 3.7 km (2 mi)**
 Damage Severity Rating, **DSR = 3**

- Portions of the trestle over Launitas Creek, about 1.6 km (1 mi) form Point Reyes, were thrown entirely off the piles, the piles themselves being moved downstream (39, pg 152).

Distance to San Andreas Fault, **R ≈ 3.7 km (2 mi)**
 Damage Severity Rating, **DSR = 3**

- At the Southern Pacific Bridge, crossing the San Lorenzo River, there is a network of fissures varying from 50 to 380 mm (2 to 15 in) in width, running thru the sandy soil. The direction of the main fissures is east and west, and they are on the south side of the river, which is nearest the Bay. The ground has settled about 250 mm (10 in) from the abutments and piers of the bridge (39, pg 87).

Distance to San Andreas Fault, **R ≈ 26 km (14 mi)**
 Damage Severity Rating, **DSR = 0**

- A railroad bridge at Lake Merced, about 9.5 km (6 mi) north of Mussel Rock was badly wrecked. Both lateral and vertical movements were extremely large, 1.5 to 4.5 m (5 to 15 ft). Evidence of liquefaction in the form of sand boils were found in the general vicinity (38, pg 251).

Distance to San Andreas Fault, **R ≈ 5.5 km (3 mi)**
 Damage Severity Rating, **DSR = 3**

- The bridge over Coyote Creek, on the Alviso-Milipitas road was severely damaged by liquefaction and lateral spreading. The concrete abutments were thrust inward toward each other about 0.9 m (3 ft). A pile driven in the middle of the stream, which had been cut off below water level, was lifted about 0.6 m (2 ft) (38, pg 281; 39, pg 113). The entire area was the location of large fissures, sand boils, and lateral streamward movements occurring as a result of liquefaction. It was also noted that another bridge crossing the Coyote Creek experienced little damage, only small movements. There is no mention of any soil failures in the area of this other (southern) bridge (38, pg 280).

Distance to San Andreas Fault (northern bridge), **R ≈ 28 km (15 mi)**

Damage Severity Rating, **DSR = 3**

- Two bridges located at Neponset over the Salinas River were damaged. The northern concrete piers of the railway bridge moved 51 mm (2 in) east, and the central wooden pier of the county bridge moved about 1.2 m (4 ft) south. Many mentions of liquefaction induced sand boils and fissures are made (38, pg 293; 39, pg 79).

Distance to San Andreas Fault, **R ≈ 26 km (14 mi)**

Damage Severity Rating (concrete railway pier), **DSR = 1**

Distance to San Andreas Fault, **R ≈ 26 km (14 mi)**

Damage Severity Rating (wooden central pier), **DSR = 3**

- At Neponset and Salinas the piling under the county bridges was moved in some bents as least 10 feet toward the river. Large sand boils were observed in the area (38, pg 293).

Distance to San Andreas Fault, **R ≈ 26 km (14 mi)**

Damage Severity Rating, **DSR = 3**

- A county road bridge over the Pajaro River near Chittenden was severely damaged by lateral spreading of sediments toward the river channel. The abutment was displaced and fractured. The damage to the concrete abutments of the county bridge across the Pajaro River is due to this crowding in of the alluvial banks of the stream. (39, pgs 22 & 85).

Distance to San Andreas Fault, **R ≈ 1.9 km (1 mi)**

Damage Severity Rating, **DSR = 3**

- The Southern Pacific Bridge across the Pajaro River, at Watsonville, consisted of four 80-ft wooden spans on pile piers, had the second pier from the east end moved up stream about 3 feet. The highway bridge at Watsonville was distorted in similar manner to the Salinas Bridge described above due to the shifting of the bank deposits (39, pg 83).

Distance to San Andreas Fault (Southern Pacific Bridge), **R ≈ 12 km (6.5 mi)**

Damage Severity Rating, **DSR = 3**

Distance to San Andreas Fault (Highway Bridge), **R ≈ 12 km (6.5 mi)**

Damage Severity Rating, **DSR = 3**

- At Port Kenyon, a large field bordering Salt River was spread open in many places, several acres of the land settling a couple feet. From its appearance it would seem that water spurted in large quantities from the ground. On the north bank of Salt River at the lower bridge the land has slid in and cracked for a distance of several hundred feet and a width of thirty to forty feet. The bridge itself does not seem to have been damaged any and is presumably in as good condition for travel as before the shock (*39, pg 170*).

Distance to San Andreas Fault, **R ≈ ? miles**
 Damage Severity Rating, **DSR = 0**

- The bridges over the Russian River, at Healdsburg, and at Bohemia, on the California Northwestern, were both shifted slightly on the piers at one end (*39, pg 160*).

Distance to San Andreas Fault (Healdsburg), **R ≈ 35 km (19 mi)**
 Damage Severity Rating, **DSR = 1**
 Distance to San Andreas Fault (Bohemia), **R ≈ 13 km (7 mi)**
 Damage Severity Rating, **DSR = 1**

- The movement at Gonzales Bridge was mostly on the west Bank of the stream. Wooden piles at the southwest end of the bridge, said to be driven down 22.8 m (75 ft), have been torn loose and moved from plumb. At the northeast end of the bridge the piles are undisturbed, but the surface soil has moved relatively 450 mm (18 in) northward (*38, pg 293; 39, pg 75*).

Distance to San Andreas Fault (SE extent of rupture), **R ≈ 44.5 km (24 mi)**
 Damage Severity Rating, **DSR = 2**

1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

Date of Occurrence:

Magnitude: $M_W = ?$

Location:

Reference: (20)

General Damage to Bridge Structures:

- A Bridge over the Ashley River was damaged. 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.

Distance to Rupture Zone, $R \approx ?$

Damage Severity Rating, $DSR = 3$

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