FOUNDATIONS AND EARTH STRUCTURES IN EARTHQUAKES

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The paper consists of four sections: foundations, earth dams, tunnels, and a preliminary statement on landslides. In the first three sections there are summarized a considerable number of instances in which earthquake damage has occurred, and generalizations are drawn where appropriate. The reported experience comes primarily from the United States, Japan, and New Zealand, and in lesser degree from Italy, Chile, Mexico, and China.

Earthquake damage to other important classes of foundations and earth structures, notably waterfront works, retaining walls, embankments, and the foundations of pavements, railways, chimneys, and tanks, are not covered herein. It is attempted in each case to summarize the pertinent features of the affected system, including soil and geologic conditions, the damage details, and the local earthquake intensity. In several instances, as will be noted, one or more of these items of data is incomplete. Intensity is expressed according to the Modified Mercalli scale of 1931, (1)** with intensities reported on other scales being converted to equivalent values on the Mercalli scale.

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FOUNDATIONS

The word "foundation," as used in this section, means the soil or rock which receives the forces which are transmitted to the earth from a structure, through a substructure of concrete or masonry footings, supported in some cases on piles.

Facts regarding earthquake damage to foundations have been reasonably well reported for a number of major bridges and for certain dramatic instances of buildings, but detailed information about minor bridges and about buildings in general is meager indeed. Covered only inferentially are earthquake damage to substructures and the effects of foundation and substructure behavior on the damage to superstructures.

Bridges

A significant aspect of the response of large bridges and their foundations to earthquakes is associated with their length and their usual location at bodies of water. Soil and geologic conditions normally are different at the ends from the conditions in the central section, and even

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** Parenthesized numerals refer to the lists of references.

within the central section there may be considerable variation among types of foundation. As a result, different motions are transmitted from ground to structure at different points, and the consequent response of the bridge-substructure-foundation system may be very complex.

In Table 1 there are summarized the earthquake damages to a number of bridge foundations. The cases presented are limited to those in which the damage is attributed to failure of the soil supporting the substructure or to the movement of soil in abutments. The experience comes from Japan, New Zealand, and California. Table 2 lists the modes of failure which have been observed.

Only one case has been found in which foundation damage was associated with a fault break. This occurred at the Pajaro River Bridge east of Monterey Bay in the great earthquake of 1906. A transverse horizontal displacement on the San Andreas fault caused a 3.5-ft. offset, resulting in relatively small settlements and secondary horizontal displacements of the piers due to their movement on their shale and sandstone foundations. A previous bridge at the same site had suffered a one-foot offset in an earlier earthquake.

Settlements of piers, ranging in amount from inches to feet. occurred at the Hozue, Old Tone, Arakawa, Westshore, Redclyffe, Hamaatsuma, Irishikabetsu, and Ainu Name bridges. In all of these cases the substructures were carried by soft soil. In the other cases of soft soil foundations, namely the Salinas, Watsonville, Yamabuki, Karamea, Wairoa, and Kuzuryu bridges, pier settlement probably occurred but was masked by the extensive horizontal or rotational pier movements. Movements of piers of several other bridges occurred in the 1906 San Francisco earthquake. Small pier settlements also occurred at the Inangahua bridge where the substructure was carried through alluvium to rock.

Abutment failure was also a commonly noted phenomenon. At the Duncan Mills, Baru, Yamashita, Yamabuki, Matakitaki, and Nakatsuno bridges, an abutment failed by displacing or tipping toward midstream. One anchorage of the Naruka suspension bridge was displaced eight inches toward midstream. All of these were in soft ground areas.

Horizontal displacements of piers due to failure of soft soil occurred transversely to the bridge axis at the Lagunitas, Old Tone, and Arakawa bridges, parallel to the axis at the Kuzuryu bridge, and in both directions at the Westshore bridge. Pier rotation due to the same deficiency was reported in the transverse direction at the Arakawa and Karamea bridges, in the parallel direction at the Baru, Yamashita, Yamabuki, Redclyffe, Wairoa, Kuzuryu, Nakatsuno, and Hamaatsuma bridges, and in both directions at the Old Tone bridge. The trestle piers of the Arakawa bridge rotated in the direction of the spread footing side of the foundations. At the Fallons, Old Tone, Baru, Yamabuki, Karamea, Hamaatsuma and Ainu Name bridges there were large transverse rotations of entire piers or bents, in some cases with accompanying large vertical movements of piles or footings without racking, in other cases with severe racking of pile bents. In the cases of the Old Tone and Westshore bridges, the pier movements were associated with a general downstream movement of the soil supporting the piers. At the Redclyffe and Hamaatsuma bridges, fissures were observed in the river beds after the earthquake.

Cases of non-damage to bridge foundations are many, though documentation is inadequate. In the southern California earthquakes of 1933 (Long Beach) (15) and 1952 (Kern County) (24, 25), such damages were almost zero. Small settlements of piers occurred at certain railroad bridges in 1933. The foundation soils of this region are markedly firmer than those supporting most of the bridges in Table 1.

Buildings

In the epicentral area of the Charleston, South Carolina, earthquake of 1886 (2), a number of instances were reported where small wood piles and brick piers, of shallow penetration in surface soils under houses, were driven several inches into the ground due to the earthquake.

At San Francisco, in 1906 (3, 4), neither the monolithic raft type nor the individual footing type of foundation at major buildings suffered noticeable differential settlement or permanent lateral movement. This applied to such buildings on soil types ranging from rock to artificial fill over deep mud. On the other hand, in the areas of the latter type of soil many three- and four-story brick buildings on "rafts" made of layers of wood plank settled extensively, the space between walls arching up "like the back of a turtle" by as much as six feet between walls 30 feet apart. Other failures occurred under houses due to shifting of underlying alluvium. A 30,000-gallon fuel oil tank on marsh land on the Bay shore, built on a timber grillage, settled two feet.

There have been many reports of extensive earthquake damage to the foundations of Japanese houses and larger old style Japanese wood buildings (20). For example, in the 1923 Tokyo earthquake there were many cases where the foundation stones under the columns of Japanese houses shifted laterally, resulting in varying degrees of collapse of the houses (5). Kanai has made a statistical study of the damages to such buildings for the great earthquakes occurring from 1891 to 1947 (18, 19). It was found that on soft marshy ground a relatively large fraction of buildings was damaged, but in most cases the damage was not total. A relatively small fraction of those on firm ground was damaged, but most of those damaged collapsed completely. He concludes that the differential settlement and lateral movements of footings on the soft ground were responsible for this effect.

In New Zealand in the 1931 earthquake (13, 14), there were many instances of settlement of footings of both wood and brick buildings on silt foundations. On firmer ground, such settlements did not occur.

No visible foundation damage or differential settlement of buildings was found at Long Beach in 1933 (15). The soil is alluvial deposits of various degrees of firmness, but is generally much superior to the soft soils of San Francisco, Tokyo, and New Zealand.

The Tonankai earthquake in 1944 in Japan caused considerable differential settlement and lateral movements of several feet at some steel and timber industrial buildings built on soft alluvium (16). In the 1946 Nankai earthquake (17), the Bunka Building in Kochi City tipped as a unit by five degrees toward the adjacent river, resulting in complete collapse. This was a three-story reinforced concrete structure.

The Daiwa Department Store in Fukui, Japan, built on shallow piles in very soft clay, suffered disastrous differential settlement in the 1948 earthquake (21). The building was six stories high, of reinforced concrete, built in three sections, and had been fire damaged in the war. The foundation failure has been attributed to insufficient capacity of piles as well as insufficient number of piles.

In another southern California earthquake, in Kern County in 1952, building foundation damage associated with soil failure was negligible (24, 25). One oil storage tank south of Bakersfield experienced settlement. Most of the structures were on moderately firm sandy alluvium.

In addition to the cases mentioned above, earthquake induced settlement and lateral movement of spread footings on soft soil contributed materially to building damage in Hokkaido in 1952 (23) and Eureka in 1954 (26).

Generalizations

The observational results presented above permit the making of a few general statements about earthquake damage to foundations. The data are not sufficiently detailed or complete, however, to permit the formulation of quantitative conclusions.

1. The type of soil is the principal determiner of damage. Settlement and lateral or rotational displacement at the substructure of bridges and buildings on soft ground have occurred in nearly all of the earthquakes reported, while foundations consisting of better soils and rock have not suffered failure.

2. The smallest Modified Mercalli intensity which has resulted in bridge foundation failure, for the cases considered here, is approximately VIII.

3. In the one case of a fault cutting a bridge, which was founded on rock, foundation damage as such was quite small.

4. A number of cases have occurred where bridge piles in soft soil have been forced deeper into the ground or partially pulled out of the ground.

5. Design implications include:
   (a) the following of good practice with respect to provision for transfer of vertical loads;

(b) the design of foundation elements for seismic horizontal forces between substructure and ground;
(c) the minimizing of earthquake induced differential settlement and relative horizontal movement of footings;
(d) the provision of features that will prevent rotation in a vertical plane of bridge piers and bents.

EARTH DAMS

Eighteen cases have been examined in which earth dams have been damaged in earthquakes. The data are summarized in Tables 3 and 4. In three of the cases, fault breaks passed through the dam, though in two cases the dam had been retired from service prior to the earthquake. In two other cases, fault breaks passed close to but not through the dam. Only two instances are known where an earth dam failed completely during an earthquake, releasing the contents of its reservoir. In all cases of damaged dams, the construction apparently was carried out without the use of modern compaction control techniques. The typical pattern of damage consisted of longitudinal cracks on or near the crest, sometimes accompanied by settlement, horizontal movement of parts of the fill, and cracking of appurtenant structures.

Two of the three dams sheared transversely by faults were located south of San Francisco in the 1906 earthquake. These were the Upper Crystal Springs and the Old San Andreas Dams, situated on the San Andreas fault, which experienced transverse offsets of about eight feet, but which were not retaining differential water heads. They retained their coherence but of course might not have done so had they been retaining water. The same fault break caused a seven foot offset in the natural ground between the two segments of the nearby in-service San Andreas Dam, but did not result in failure. The Saratoga reservoir, situated on and experiencing transverse movement of this fault through the two dams, lost its retained water but did not fail completely. Another case of nearby faulting occurred with Hebgen Dam, Montana, in the 1959 earthquake. Here, the dam suffered differential settlement seemingly associated with the vertical fault movement beyond its north abutment, but it did not fail.

The Sheffield Dam, retaining a reservoir near Santa Barbara, California, failed due to shaking in the 1925 earthquake. Apparently the lower portions of this structure were saturated with seepage water. The manner in which the failure progressed is not known, but it appeared as if the 300-foot segment which slid out near the center, moving 100 feet or more down stream, had yielded more or less in a body, crumbling due to the strain and being further broken up and transported by the rushing waters. The other case of complete failure was the Augusta Dam, in 1886, which cracked transversely in the earthquake and subsequently failed due to erosion through the cracks.

In general, all damaged dams exhibited longitudinal cracking on the crest. The Ono and Lower Murayama dams near Tokyo showed such effects in the 1923 earthquake, as did the Otaniike Dam in Shikoku in 1946. In two hydraulic fill structures affected by the 1952 Kern County, California, earthquake, the crack patterns had curved shapes in the central portion. In the Dry Canyon Dam, an exploration pit showed that the crack extended into the impervious core and curved in a vertical transverse plane toward the reservoir. Settlement measurements supported the concept of incipient sliding on the upstream side. The crack pattern at South Haiwee Dam appeared as a flat arc in the horizontal plane, with the convex side upstream. On the other hand, the cracks in Hebgen Dam, which has a concrete core wall, were near the abutments, implying differential horizontal displacements at the ends. The cracks at the abutments of San Andreas and Ono dams also suggest the latter kind of movement.

At the Yuba Dam in central California, an earthquake in 1951 triggered a slide on the downstream face. High pore pressure is believed to have existed behind the slide surface before the earthquake. Lower Murayama Dam experienced slumping of the slopes in the 1923 Tokyo earthquake.

Kawakami (49) has presented the following statistical summary of the damage to 53 earth dams in the Oga earthquake of 1939. The affected area was on the northwest side of Honshu, Japan, opposite the city of Sendai. The magnitude was 6.6 on the Richter scale and there were 604 collapsed houses and 29 deaths. The dams apparently served principally to retain agricultural reservoirs. The figures total more than 53 as more than one type of damage occurred at most of the dams.

Type of Damage	Number of Cases
Cracks parallel to crest	43
Cracks perpendicular to crest	5
Collapsed; cause unknown	7
Damaged; type unknown	2
Slumping of slopes; no cracks	1
Slumping of slopes; also cracks	
Upstream slope	17
Downstream slope	6
Both slopes	8
Cracks; no slumping	16

Damage was widespread in Kern County, 1952, to uncompacted earth embankments five to twelve feet high used to store irrigation water (42). Characteristic effects were longitudinal cracking on the crest, slumping of inner slopes, and large settlements.

The large settlements noted in certain cases in Table 4 seem to be associated with poor foundations. Approximately half the length of Hebgen Dam, the earth part of which settled about four feet, is located on an old landslide. At Buena Vista Dam, near Bakersfield, California, the portion which settled about two feet in the 1952 earthquake is believed to be underlain by gypsum bearing soil containing many cavities leached by percolating water. The small earthquake-induced settlements of Cogoti, Tokyo Water Supply, Upper Murayama, and Piedmont No. 2 dams are not considered as important damage.

An opportunity to study the value of controlled compaction of fill occurred in the 1952 Kern County, California, earthquake. The completely sound condition of Tejon Ranch Dam (24), built with careful attention to the principles and techniques of compaction, may be compared with the damage to Buena Vista Dam, which was farther from the epicenter though on an admittedly poorer foundation. Similarly, the controlled-compaction Bouquet Canyon Dam (41) experienced no damage, while Dry Canyon Dam, at a comparable epicentral distance, suffered important cracking and settlement.

It is of interest to note the relatively small amount of earth dam damage in the 1952 Kern County earthquake. A total of three older dams was injured, whereas there were some 80 earth and rock fill dams in Kern County and the adjacent counties which felt strong shaking (43). Of the three injured dams, Buena Vista was near the epicenter, but both Dry Canyon (Intensity VII) and South Haiwee (Intensity VI) were at epicentral distances of the order of 60 miles. Within this 60 mile radius there were approximately six other earth dams. A similar comparison may be made with respect to the 1906 San Francisco earthquake, where four dams experienced damage associated with shaking. The nearby Pilarcitos and Bear Gulch earth dams and the Piedmont No. 1, Lake Frey, San Leandro, and Temescal earth dams across the bay escaped damage (29, 40, 4).

From the above summary of earth dam performance in earthquakes, it may be stated that:

1. Dams designed and built in accordance with modern practice, which calls for controlled compaction of selected materials, preventing of excessive pore pressures and seepage, relatively flat slopes, firm foundations, and provision for resisting lateral seismic force, have not been damaged in earthquakes.
2. Damage is inevitable when a large fault displacement crosses a dam. Whether complete failure might occur due to this effect can not be stated from experience to date.
3. The minimum intensity of shaking to produce damage to the older dams appears to be about VII on the Modified Mercalli scale, though three cases are reported where damage resulted with Intensity VI. Two cases exist in California (1906 and 1952) where there were more undamaged than damaged dams in the epicentral areas.
4. In checking a dam for earthquake resistance, the engineer should consider the following possible modes of failure:
    a. the sliding of part or all of the upstream or downstream face, including in the analysis the extreme possible conditions of pore pressure and saturation;
    b. the longitudinal cracking of the dam due to earthquake-induced distortion;
    c. the transverse displacement of the dam with respect to its abutments;
    d. the settlement of the dam or its foundation;
    e. the loading of conduits, spillway, intake, and other appurtenances by differential movements of soil;
    f. the possibility of fault movement crossing the dam;
    g. the scouring effects of earthquake-induced water waves.

TUNNELS

Four reasonably well documented cases of earthquake damage to tunnels are presented, along with supporting and indirect evidence. The details of the failures and of the geology are less complete than is desirable, but the facts available appear to warrant several useful generalizations. The subject has been treated elsewhere in fuller detail (60).

In the San Francisco earthquake of 1906, there were two damaged timber-lined tunnels on the narrow-gage Southern Pacific Railroad between Los Gatos and Santa Cruz (3, 4, 32). The 6200-ft. tunnel at Wright Station was crossed by the San Andreas fault and the 5700-ft. tunnel directly to the south was also damaged, but to a somewhat lesser degree. Shaking at the surface over the tunnels is designated X on the Modified Mercalli scale. Damage consisted of the caving-in of rock from the roof and sides, the breaking in flexure of upright timbers, and the upward heaving of rails and breaking of ties. Other tunnels on the Santa Cruz-Los Gatos line were undamaged except for two cases of broken timbers. New tunnels under construction on the Bayshore line, in southern San Francisco, were uninjured. A tunnel collapsed in a quicksilver mine near Guerneville, killing three men (61).

The tunnel at Wright Station suffered a 4.5 ft. transverse horizontal offset where the fault cut it. Tunnel damage was greatest around the offset and at the several locations where parallel fissures were in evidence. The rocks were sandstones and jaspers. Also, brick-lined conduits in the San Andreas and Upper Crystal Springs earth dams were shattered (34).

The great 1923 earthquake damaged about 25 tunnels in the vicinity of Tokyo, principally on the Izu and Boso peninsulas which are the mainland areas closest to the epicenter (51, 52). The damage is attributed to shaking, as no case of faults intersecting the tunnels is known. Most of the tunnels were concrete or brick-lined, with depth of cover, character of rock, length, and other features varying over a rather wide range. Damage varied from negligible to fractured portal masonry, cracked linings, and cave-ins from roof and sides. Particularly heavy tunnel damage occurred in the Odawara-Atami-Hakone region, which suffered the highest intensity of shaking. Beyond the isoseismal corresponding to approximately 50 per cent of houses collapsed, tunnel damage apparently was insignificant.

The Tanna Tunnel, connecting Atami and Mishima, Japan, was under construction during the Izu earthquakes in 1930. The Tanna fault intersected one of the drain tunnels which extended ahead of the main tunnel heading, causing a transverse horizontal offset of 7.5 ft. at a distance of about two feet beyond the main tunnel heading (53, 54). The only damage to the tunnel was a few cracks in the walls. But in the village of Karuizawa, situated on the Tanna basin 500 feet above the tunnel, 55 per cent of the dwellings were thrown down, and 40 per cent of the houses were destroyed at the nearby villages of Tanna and Hata. Surface displacements on the fault occurred over a distance of nine miles. The Tanna basin is a lake deposit of sandy clay and boulders, about 40 meters deep, overlying andesite and agglomerate through which the tunnel passes.

The Kern County earthquake of 1952 severely damaged four tunnels on the Southern Pacific Railroad near Bealville, about 15 miles northwest of Tehachapi (24, 55, 56). This was the region of largest observed ground fractures associated with movement on the White Wolf fault. While these tunnels were in the region of heaviest shaking, Modified Mercalli Intensity XI, the extensive damage was primarily due to their location in this fault zone. In all, there were 15 tunnels between Bakersfield and Tehachapi, and those outside of but adjacent to the area of ground fractures suffered slightly, to the extent of opening of construction joints. The railroad in this area was built about 1876, with timber lining in the tunnels. Reinforced concrete lining 12 to 24 inches thick was installed later without removing the timber. Rock around the four damaged tunnels was a fairly easily excavated decomposed diorite.

Tunnel No. 3, originally 700 ft. long, was heavily damaged at its Tehachapi end, 200 ft. of which was daylighted after the quake. While ground cracks were not found directly over No. 3, an active fault crossing the tunnel was found during daylighting. Large surface cracks were found above No. 4, which was badly shattered and subsequently daylighted for its full length. No. 5 was very heavily damaged but was reconstructed without daylighting. Cracks and holes appeared in the ground above, and rock and soil from these cracks flowed into the tunnel. Broken lining comprised the damage to No. 6, which was daylighted.

At Kumasaka, Japan, the portal arches of a brick-lined tunnel were partially fractured in the 1948 Fukui earthquake (21). Also in this earthquake, a large concrete culvert was badly cracked at midlength. In the 1952 Hokkaido earthquake, minor cracking was induced in the walls of one concrete-lined and one brick-lined tunnel (22).

Except for the 1906 and the 1952 cases, no damage or disturbance to Southern Pacific Railroad tunnels has been caused by earthquakes (57). The Pacific Gas and Electric Company has found no significant earthquake damage to tunnels in its 40 years of experience with 73 tunnels, unlined and concrete lined, totaling 119 miles in length (59). The Los Angeles Department of Water and Power operates the Owens Valley Aqueduct, which includes 142 tunnels totaling 43 miles in length. The Aqueduct was completed in 1911, and no tunnel damage due to earthquakes has occurred (58). The San Francisco Water Department has reported that there has been no earthquake damage to its 66 miles of tunnels except as described above (62). Similarly the California Department of Water Resources reports no earthquake damage to 100 California tunnels, each 1000 ft. or more in length, except as indicated in this paper (62). These negative data are significant in view of the fact that California has suffered severe earthquakes in 1915 (Imperial Valley), 1925 (Santa Barbara), 1933 (Long Beach), 1940 (El Centro), 1952 (Kern County), and 1954 (Western Nevada), in addition to the great earthquake of 1906. Similar negative data come from the New Zealand earthquakes of 1929 (Murchison), and 1931 (Napier) (12).

The following generalizations may be drawn from the experience reported:

1. Severe tunnel damage appears to be inevitable when the tunnel is crossed by a fault or fault fissure which slips during the earthquake.
2. In tunnels away from fault breaks but in the epicentral region of strong earthquakes, severe damage may be caused by shaking, to linings and portals and to the surrounding rock, when construction is of marginal quality.
3. Tunnels outside the epicentral region, and well-constructed tunnels in this region but away from fault breaks, can be expected to suffer little or no damage in strong earthquakes..
4. While it would seem reasonable that competence of the surrounding rock and soil would reduce the likelihood of damage due to shaking, inadequate comparative evidence is available on this point

LANDSLIDES

Data on the triggering of landslides by earthquake action have been collected by the author's associate, David J. Leeds, from a large number of earthquakes. A future paper will present the data and interpretations. Reports vary from bare mention of the earthquake-triggered landslide to detailed engineering-geologic discussion. The study included over 165 landslides or landslide areas resulting from 54 earthquakes spanning almost fourteen centuries. The slides range from a few inches of creep to massive rock falls weighing millions of tons and covering hundreds of square miles.

There is multiple evidence that earthquakes and landslides occur concurrently, but that by far the predominant number of landslides are not earthquake triggered. Most scales of earthquake intensity include the occurrence of landslides as an index of intensity of the more destructive earthquakes. There are also cases reported of slides being triggered in areas of low intensity. Sensitivity of the slope exercises as strong a control over sliding as does seismic shaking. In the absence of steep mountain slopes great earthquakes have also caused landslides in flat, plain areas.

From the Tosa disaster in 684 where numberless dwellings, shrines, and temples were destroyed by landslides and countless people were killed, to the Montana experience in 1959 which claimed 22 lives, earthquake-produced landslides have taken a heavy toll of life and property.

From the factual summary developed by Leeds, the following tentative generalizations are advanced:

1. Landslides occur as a result of many interacting causes, among which earthquakes occasionally act as the direct cause or trigger.
2. Earthquakes of Intensity VI or greater on the Modified Mercalli scale usually trigger landslides. In some cases intensities as low as IV have set off landslides. The incidence and severity of landslides increase with intensity.

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Table 1

Bridge Foundation Failures in Earthquakes

Earthquake. Intensity.* (Reference.)	Bridge Name and Location	Bridge Features	Modes of Failure**
1906 San Francisco X (4)	Pajaro. Chittenden, Calif.	Railroad bridge. Masonry piers on shale and sandstone.	1, 2, 5, 6.
X (4)	Duncan Mills. Coast north of San Francisco.	120 ft. span.	3.
IX (4)	Fallons. Coast north of San Francisco.	Trestle 600 ft. long, 70 ft. high, of framed bents on piles in marshy ground.	8.
VIII (4)	Lagunitas. Near Point Reyes.	Trestle on piles in marshy ground.	6.
VIII-IX (4)	Salinas. Salinas.	Wood truss highway bridge on wood pile bents in alluvium.	7.
VIII-IX (4)	Watsonville. Watsonville.	Wood truss highway bridge on wood pile bents in alluvium.	7.
1923 Tokyo IX (9)	Hozue. North of Tokyo.	Timber road bridge on five-pile bents in very soft soil.	2.
IX (9)	Old Tone. 30 km. north of Tokyo.	Steel truss road bridge. Brick abutments. Pile bents. Piles up to 30 ft. long. Soil very fine sand.	2, 4, 6, 7, 8.
VII (9)	Baru. 50 km. southwest of Tokyo. Under construction.	Reinforced concrete road bridge on reinf. conc. bents set in wells filled with gravel or unhardened concrete.	3, 7, 8.
X (10)	Yamashita. Yokohama.	Road bridge. Masonry pier and abutment foundations carried to rock. Both banks very soft reclaimed land.	3, 7.

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* Expressed in terms of the Modified Mercalli Scale of 1931. In most cases, values have been scaled from isoseismal maps.

** See Table 2.

Earthquake. Intensity. (Reference.)	Bridge Name and Location	Bridge Features	Modes of Failure
X (10)	Yamabuki. Yokohama.	Trussed steel road bridge. Bents in softest soils in Yokohama.	3, 7, 8.
VIII (11)	Arakawa. 10 km. northeast of Ueno Station, Tokyo.	48-span trestle with old railroad track on spread footings, new track on piles. Four-span bridge near middle. Masonry piers on presumably marshy soil.	Trestle: 2, 6, 8. Bridge: 2, 6.
1929 Murchison. IX (12)	Matakitaki. Murchison, New Zealand.	Steel bridge on concrete piers on piles.	3.
VII-VIII (12)	Inangahua. 20 miles east of Murchison.	Concrete piers on concrete cylinders carried to rock through alluvium.	2.
VIII (12)	Karamea. 35 miles north of Murchison.	Timber trestle on piles driven 10-15 ft. in "fairly tight puggy clay."	8.
1931 Napier. IX (12)	Westshore. Napier, New Zealand.	Concrete bridge and piers on concrete piles driven 25 ft. in marine silt interspersed with gravel.	2, 4, 5, 6.
IX (12)	Redclyffe. 5 miles southwest of Napier.	Timber bridge on wood piles driven in dirty gravel formation overlying limestone.	2, 7.
VIII (12)	Wairoa. 40 miles northeast of Napier.	90-ft. concrete cylinder piers in very soft mud.	7.
1948 Fukui. XI (21)	Kuzuryu. 3 miles north of Fukui.	Electric railroad bridge. Piers on 18-ft. piles in soft clay.	5, 7.
X (21)	Naruka. 7 miles northeast of Fukui.	Railroad suspension bridge founded in soft clay.	3.
XI (21)	Nakatsuno. 3 miles north of Fukui.	Steel highway bridge on concrete piers on piles in soft clay.	3, 7.
1952 Hokkaido. VII-IX (22)	Hamaatsuma. 12 miles east of Tomakomae, Japan.	Timber highway trestle on concrete rigid frame bents. Ground is alluvium.	2, 7, 8.

Earthquake. Intensity. (Reference.)	Bridge Name and Location	Bridge Features	Modes of Failure
VII-IX (22)	<u>Irishikabetsu</u>. 11.5 miles east of Tomakomae.	Timber highway trestle on pile bents. Ground is peat beds and alluvium.	2.
VII-IX (22)	<u>Ainu Name</u>. 11 miles east of Tomakomae.	Timber highway trestle on pile bents. Ground is alluvium.	2, 8.

Table 2

Modes of Failure of Bridge Foundations

1. Fault intersected bridge axis, causing relative transverse displacement.
2. Bents or piers settled.
3. Abutments moved or tipped toward midstream.
4. General transverse movement of soil supporting piers.
5. Bents or pier foundations displaced longitudinally.
6. Bents or pier foundations displaced transversely.
7. Bents or pier foundations rotated in longitudinal vertical plane.
8. Bents or pier foundations rotated in transverse vertical plane.

Table 3

Description of Earth Dams

Name, Location Year Built	Dimensions and Features	Materials
Augusta. Northeast of Augusta, Georgia.	Water power dam on a tributary of Savannah River.	Earth fill. Ground in area was loose soil, thinly covering hard rocks below.
San Andreas. South of San Francisco. 1875.	97 ft. high. Crest 25 ft. wide. Slope 3.5:1 upstream, 3:1 downstream. Two crest segments 705 and 192 ft. separated by natural ground ridge.	Fill is bluish color residual of serpentinized perodotite. Founded on 46 ft. of stratified sand, clay, and gravel overlying rock. Central puddle wall carried to rock.
Upper Crystal Springs. South of San Francisco. 1877.	90 ft. high. Water level same on both sides of dam due to construction of another dam downstream.	Earth fill with clay puddle core carried into tight blue clay. Foundation clay and gravel.
Old San Andreas. South of San Francisco. Before 1875.	Crest 180 ft. long. 51 ft. brick spillway. Fully submerged, behind another dam.	Earth fill.
Saratoga. Near Saratoga, California.	Two small dams closing the two ends of a saddle. Reservoir full.	Earth fill.
Piedmont No. 2. Northeast of Oakland, California. 1906.	Just finished. Reservoir full. 6-inch concrete upstream facing.	Earth fill placed in thin layers, moistened, and rolled.
Ono. 60 miles west of Tokyo. 1914.	121 ft. high. Crest 850 ft. long.	Earth fill with clay core. Founded on paleozoic rock but left abutment on alluvium.
Tokyo Water Supply. 15 miles west of Tokyo. Jan. 1923.	79 ft. high. 18,400,000 cu. meters capacity reservoir.	Earth fill placed in 6-inch layers, rolled to 4-inch thickness. Core wall of clay and gravel.
Upper Murayama. 12 miles west of Tokyo. 1923.	Just finished. Reservoir probably empty.	Earth fill.
Lower Murayama. 12 miles west of Tokyo. 1923-24.	Under construction, 52 ft. high. Designed for 98 ft. height, 1920 ft. crest. Reservoir empty.	Earth fill with core wall. Founded on tertiary formation.
Sheffield. East	30 ft. high. Crest 20 ft. wide.	Hydraulic fill.* Probably

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* This information from Reference 37, but Reference 50 indicates that the dam was built of pit run material from the reservoir excavation, compacted by running construction equipment over the fill.

Name, Location Year Built	Dimensions and Features	Materials
of Santa Barbara, California.	Slope 2.5:1 upstream and downstream. Water depth 20 ft.	partly saturated at time of earthquake. Built in or on bouldery alluvium overlying sandstone.
Cogoti. Chile. 1938.	246 ft. high. Slope 1.6:1 upstream, 1.8:1 downstream. Designed for earthquake resistance.	Rock fill. Flexible watertight upstream face.
Otaniike. Shikoku, Japan. 1920.	69 ft. high. Crest 24 ft. wide. Slope 4:1 upstream, 3:1 downstream. Water depth 49 ft.	Earth fill with center impervious core. Founded on sandstone.
Yuba. East of Nevada City, California. 1910, 1949.	25 ft. high. Crest 880 ft. long, 12 ft. wide. Slope 2.5:1 upstream, 1.75:1 downstream. In 1949, addition made to crest and downstream slope. Reservoir full.	1910 segment earth fill derived from local porous igneous formation. 1949 addition was less permeable, mechanically compacted. High pore pressures suspected behind addition. Founded on clay.
Buena Vista. Southwest of Bakersfield, California. 1890, 1927.	17 ft. high. Crest 5 miles long.	Earth fill. Clay core added in 1927 over part of length. Foundation contained gypsiferous cavities.
Dry Canyon. North of Saugus, California. 1912.	64 ft. high. Crest 560 ft. long, 20 ft. wide. Slope 2.5:1 upstream, 2.2:1 downstream.	Hydraulic fill.
South Haiwee. South of Owens Lake, California. 1912.	90 ft. high. Crest 1500 ft. long.	Hydraulic fill.
Hebgen. Northwest of West Yellowstone, Montana. 1913.	86 ft. high. Crest 721 ft. long, 20 ft. wide. Slope 3:1 upstream, 2.5:1 downstream. Concrete core wall carried to rock.	Earth fill. North portion rests on old landslide. 12 ft. water waves broke over dam in earthquake.

Table 4

Earthquake Damage to Earth Dams

Name of Dam. Year of Earthquake. Intensity.* (References.)	Earthquake Effects
Augusta. 1886. VIII (2)	A number of large transverse cracks developed and were widened by erosion, resulting in a serious flood downstream.
San Andreas. 1906. X (29, 31, 32, 33, 34, 40)	Seven ft. horizontal transverse fault displacement through natural ground separation. Cut and shattered masonry tunnel in separation. Intake tower demolished. Small longitudinal cracks on crest. Cracks on banks at both abutments perpendicular to crest. No repairs needed to dam itself.
Upper Crystal Springs. 1906. IX (29, 31, 32, 33, 34)	Eight ft. horizontal diagonal fault displacement through east end, where crest was 20 ft. above rock. Brick lined conduit shattered over 20 ft. length. Dam shortened normal to the fault. No repairs needed to dam itself.
Old San Andreas. 1906. X (29, 30)	Seven ft. horizontal transverse fault displacement. Two-inch crack in spillway.
Saratoga. 1906. IX (3, 4)	Fault cut transversely through both dams. North dam also had a longitudinal crack and some settlement of inner slope. Reservoir emptied due to fracture of 10 inch cast iron outlet pipe in south dam, with accompanying erosion of inner slope.
Piedmont No. 2. 1906. VII (4)	Settled six inches at center. A few small transverse and longitudinal cracks near one end. Concrete facing undamaged.
Ono. 1923. VIII (35, 36, 47)	Longitudinal cracks on both slopes. Major crack near left abutment. Largest crack 8 inches wide, 30 ft. deep, on downstream slope. Crest settlement up to 8 inches.
Tokyo Water Supply. 1923. VIII (48)	Dam settled 8 inches.
Upper Murayama. 1923. VIII (47)	Crest settled 8 inches. Some slumping of slopes. No cracks.
Lower Murayama. 1923. VIII (35, 36, 47)	Three longitudinal cracks near crest. A few slumps on banks. Largest crack 220 ft. long, 30 ft. deep.
Sheffield. 1925. VIII (37, 50)	A 300-ft. length slid downstream about 100 ft., emptying the reservoir.

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* Expressed in terms of the Modified Mercalli Scale of 1931. In most cases, values have been scaled from isoseismal maps.

Name of Dam. Year of Earthquake. Intensity.* (References.)	Earthquake Effects
Cogoti. 1943. VIII-IX (38)	Dam had settled 13.5 inches since construction. Settled 15 inches more during earthquake. Subsequent settlement negligible.
Otaniike. 1946. VI (39)	250 ft. longitudinal crack on crest. Other cracks on upstream face parallel to crest. Culverts damaged in base and in left abutment.
Yuba. 1951. VI (40)	Slide 75 ft. wide occurred on downstream face, extending 35 ft. beyond toe of dam.
Buena Vista. 1952. VII-X (24)	Settlement of 2.2 ft. over 100 ft. of length. 2200 ft. longitudinal crack on crest. One incipient slide. Leak developed at south end.
Dry Canyon. 1952. VII (24, 41, 42)	Longitudinal cracks along most of length of crest, 5 ft. from downstream edge, extending into hydraulic core and curving down toward reservoir. Crest settled 0.18 ft. and moved 0.21 ft. toward reservoir. Old cracks reopened in concrete facing.
South Haiwee. 1952. VI (24, 41)	Longitudinal cracks over 250 ft. of crest near upstream face and center of crest, in flat horizontal arc concave downstream.
Hebgen. 1959. VII-IX (44)	Fill settled 4 ft. on both sides of core wall. Core wall displacement varied from 0 to 1 ft. horizontally and vertically. Some longitudinal cracks on crest near abutments. Spillway shattered by shaking and water scour. Some erosion of downstream slope. 15 ft. vertical fault displacement about 500 ft. north of north abutment.