RECENT STRONG MOTION EARTHQUAKES AND RESULTING DAMAGE

(SESSION V)

The questions not answered in a written form by the author do not appear on the pages of discussion.

ON THE SEISMIC BEHAVIOUR OF EARTH DAMS

by N. N. Ambraseys *

Introduction. Full realisation of the potential advantages of earth and rock-fill dams are sometimes seriously handicapped by the lack of suitable methods to deal with the seismic stability of such structures. If the need for research in this field of Soil Mechanics is not at once obvious, it should be noted that of the limited number of dams and of the large number of levees and roadway embankments which have been subjected to comparatively strong earthquakes, a great percentage of the former were severely damaged while, without exception, all embankments and levees were completely destroyed.

There was, and still is, however, a great deal of divergence in opinion among engineers as to whether such structures in seismic regions should be especially designed to resist earthquakes. Many believe that in an adequately designed earth dam the inherent factor of safety against slip under static conditions is ample to provide against earthquake shocks; a statement which is most probably based on the spectacular performance of the earth dams on the San Andreas fault, which although sheared during the 1906 Californian earthquake, did not fail. Experience, however, has repeatedly proved that earth dams are adversely affected by seismic shocks, and that although they may fare better than other types of dams, unless they are especially designed to withstand seismic forces, severe damage or total collapse may occur.

A completely satisfactory method of computing the seismic stability of earth dams has not been developed, and the current methods of design can at the best be considered as highly empirical. A systematic and rational development of the earthquake resistant design of earth and rock-fill dams would stem from the knowledge of the actual behaviour of such structures during an earthquake.

Since several sets of conflicting statements concerning the effects of earthquakes on earth dams have been reported in literature, and also since such reports are widely scattered in literature, not readily available to the engineer, it was considered desirable to present here, briefly, a summary of the available information. To this information, it is hoped, more will be added through discussion.

The data which the present paper contains has been extracted from a large number of references and private communications. Owing to lack of space only the more important references are included. For the same reason the cases considered are discussed briefly, without any comments on the soil properties of the structures or the effects of microregionalisation at the dam sites. Limitation of space does not permit conclusions to be drawn from the data presented.

The cases have been arranged chronologically. For each region, the epicentre, magnitude and maximum intensity, as cited in the most appropriate references, is given. Magnitudes originally given in the Rossi-Forel scale were not converted to equivalent M. Mercalli gradings since for the purpose intended such a conversion would lead to erroneous results; in particular

* Lecturer, Dept. of Soil Mechanics, Imperial College of Science, University of London, London, S.W. 7.

for the x-th Rossi-Forel grade. Table I gives some of the structural data, seismic behaviour and earthquake effects on the dams considered in this paper. In column P of the Table the estimated seismic intensity, given as a percentage of the acceleration due to gravity, does not necessarily correspond to the values of column O, as they can be converted either by means of Gutenberg's or Cornwell's empirical formulae. The values in column P were deduced mainly from microregionalisation data, wherever these were available, and by and large do not differ greatly from the values one could obtain using Gutenberg's empirical formula.

Space does not permit me to thank individually many of those who sent private communications but the author is very grateful for their help.

I) SAN FRANCISCO EARTHQUAKE, April 18, 1906.

Epicentre* 38 00N, 123 00W, Magnitude 8.3, Intensity X RF.**

1) San Andreas Dam. Figure 1 shows the course of the San Andreas fault in the San Francisco Bay Region. The fault enters the San Andreas reservoir and follows the northeast side of the lake to San Andreas earthdam. A few hundred yards northwest of the dam the fault passes at a distance of 5 feet only from a gate-well 26 feet in diameter. The walls of the structure were about a foot thick and were strongly buttressed. As a result of the shock this gate-well was shattered and deformed so that it became oval in plan, with its east-west diameter elongated to 30 feet. A concrete gate-well 15 feet from the fault nearby was undamaged although a branch crack of the fault was found to run under the structure. Upon another crack, about 45 feet from the fault, a concrete shaft was similarly unaffected.

The San Andreas dam consists of two embankments separated by a rocky knoll which served as a common abutment for both embankments. At the San Andreas earth dam the fault passed through the common abutment knoll and did not intersect either of the embankments.

This earth dam was built in 1870 and the construction practice used at the time is described by Schussler (1906). A cut-off trench was carried down to solid rock and in this trench a concrete wall was built. The top of this wall was brought up to a point somewhat above the stratum of hardpan or disintegrated rock upon which the lower portion of the puddled clay core, 20 feet in width, was constructed. The properties of the core material are not known. The fill material, however, is known to have been a residual soil from the blue greasy-textured serpentine comprising the east valley wall, Lawson (1914). The properties of the fill material were discussed by Sherard (1953). The foundation material immediately below the dam consists of a gravelly stratum mixed with sand and clay varying in thickness between a few feet near the abutments to about 39 feet at the deepest point. The bedrock material underlying the hardpan is composed on the northeast side of serpentinised periodite and on the southwest of basalt and diabase. These

---

* When the plane of rupture is of small extent, as frequently happens, the epicentre may be considered as the main source of disturbance. In the present case, however, the plane of rupture was more than 270 miles long and the conception of the epicentre as the main seat of disturbance becomes a misnomer.

** Rossi-Forel scale. Maximum seismic intensity.

two rock formations are separated by the fault plane.

Prior to the 1906 earthquake no stability or seepage troubles had been encountered and in fact in 1875 the dam was raised by 18 feet.

During the 1906 earthquake, the fault passed through the knoll dividing the two embankments. The knoll was shattered and the road and fence over the dam were offset by about 7 feet. The dam showed a severe distortion for a distance of more than 150 feet. Cracks were found to run parallel to the crest as well as in a transverse direction near the central abutment. One of the worst cracks ran diagonally across the dam and under a culvert which was however not damaged. A crack about 3 inches wide was found to extend longitudinally along the center line for the entire length of the dam. Cracks were also developed on the surface of the roadway along the top at both edges of the puddle core. These cracks could be interpreted to indicate some relative displacement, probably a settlement of the material comprising both the upstream and downstream parts of the dam on each side of the core. Some severe cracks, transverse to the line of the dam were observed in the originally undisturbed firm rock of the knoll.

Along the downstream toe of the dam, no evidence of any leakage was observed. The dam has been in constant service up to the present time, and the only reconstruction necessary after the 1906 shock was the resurfacing over the knoll. In 1928 the dam was raised 6 feet, and the crest now is above the level of the knoll, and hence the structure is no longer divided at this point.

2) Upper Crystal Springs Dam. From the San Andreas dam the fault enters the Crystal Springs reservoir and passes through the Crystal Springs earth dam, crossing it practically at right angles. This dam was built in 1878 and it is of similar construction to the San Andreas dam. At the time of the 1906 shock this dam was simply a causeway across the reservoir, the water on both sides of the dam standing at the same level (equalising pipes having been placed through it).

The dam is founded on the northeast side of the fault on bedrock composed of serpentinised periodite, while on the southwest on the old alluvial formation of Santa Clara, Lawson (1914). This formation, which at some places is probably 300 feet thick is a rudely stratified alluvial fan deposit of angular fragments of rock and waterworn pebbles.

No account of the original construction was found. It was probably built in the same manner and of the same material as the San Andreas dam.

Where the fault intersected the dam, the structure was dislocated and offset by about 8 feet. Longitudinal and transverse cracks appeared on the top of the dam, and some of the former, about 6 inches wide, were found to extend to a depth of 4 feet. The transverse cracks were less well defined and indicated a general distortion on each side of the fault line. The facts indicate also that in addition to the offset of the dam along the line of the fault, there was a considerable compression in the direction normal to it. The compression was concentrated close to the fault. The crest of the dam on the fault plane was less than 20 feet above the rock foundation. Some of the apparent distortion was considered to be associated with the raising of the dam a few years earlier. The additional 7 feet of fill placed at this time was not as carefully compacted as that in the main part of the dam. This additional fill and the high level of saturation line resulting from the dam being submerged on both slopes are probably accountable in large part for the formation of longitudinal cracks through a tendency of the slopes to slump.

Many engineers consider that the dam cannot be classified as being damaged by the earthquake, while others disagree. Henny (1932) for instance, as he recalls the condition of the dam after the shock stated that there were several shear cracks parallel to the plane of the fault; he also described numerous longitudinal cracks extending on each side of the fault along both the top and faces of the dam. The fact that this structure was claimed to have resisted the earthquake presented in his opinion too optimistic a picture which he considered desirable to correct. If the dam had not been submerged on both sides, the cracks across the dam, he believed, would have certainly caused failure. To what extent the earthquake of 1906 tested the ability of this earth dam to retain water is difficult to say.

3) Old San Andreas Dam. In 1931, when the water of the Crystal Springs reservoir was lowered, this dam was uncovered. The Old San Andreas dam is located in the Crystal Springs reservoir about one mile north of the Crystal Springs earth dam. At the time of the 1906 earthquake this earth dam was completely submerged, and when uncovered in 1931 it was found that an offset had occurred due to the fault movement. The fault passed through the dam at right angles to the crest and about 30 feet from the east spillway. The displacement along the fault was about 7 feet. The only visible damage to the dam was a crack 2 inches wide extending vertically up the brick face of the spillway. Nothing is known of the construction and foundation material of this dam.

4) Lake Ranch Dam. The fault intersects another earth dam at about 2 miles south of the village of Congress Springs. This structure, the Lake Ranch dam, was built in 1877 and no description of the dam construction has been found. The 1906 fault movement did not intersect the main structure but crossed a small subsidiary dyke about 3 feet high. The water in the reservoir is said to have had run over this dyke, but no damage to the main structure was reported. A short distance to the northwest of the dam an elevated water tank was found undamaged, and houses at the south end of the dam lost only the wall plaster of the ground floors.

5) Upper Howell Dam. Further south the fault intersects the Upper Howell earth dam at right angles. The fault runs through the reservoir crossing the dam near its east abutment. Cracks were formed at this point which extended through the body of the dam. There was also a longitudinal crack on top of the structure and considerable settlement of the upstream face. No detailed account of the construction and foundation material was found.

6) Lower Howell Dam. The fault also intersects the Lower Howell dam. A breach 4 to 6 feet wide was formed through the body of the earth dam. A 10-inch outlet pipe in the area of the breach was broken by the fault and considerable damage seems to have been done to the dam from the water which escaped from this pipe. Whether the dam itself would have been seriously damaged by the earthquake if this pipe had not broken could not be determined. It is noteworthy, however, that the fault at this point produced very little displacement and the seismic intensity was comparatively low. The dam was built in 1877 and practically nothing is known of its construction.

7) Name not known (I) In the vicinity of the fault, near the Howell dams an unindentified composite earth-concrete dam was reported to have failed. This structure is said to have been built partly on embankment and partly in excavation.

8) Bear Gulch Dam. Southeast of the Crystal Springs earth dam, about two miles northeast of the fault is the Bear Gulch dam. The original structure a

homogeneous embankment, was built in 1896 of medium plastic clay of fluvial origin, and the construction method employed at the time was probably the same as for the San Andreas dam. The foundation is composed of soft sandstone and shale dipping a few degrees downstream. No difficulties were reported during construction, and although nothing is known of its behavior during the 1906 earthquake it can be inferred that the dam was not damaged. The seismic intensity at the site was rather low. Nevertheless, the water in the reservoir was reported to have been thrown over and about 25 feet beyond the crest of the dam. Water pipes leading from the reservoir to the town of Menlo Park were pulled apart. In 1929 the dam was raised by 18 feet and 1936 a shallow slide some 3 feet deep developed on its upstream face.

9) Lagunita Dam. Although the shock at the site was rather severe, no damage was reported to have been sustained by the Lagunita earth dam located about 4 miles northeast of the fault, near Stanford. This high intensity at a point more than 3 miles from the fault and beyond a zone of lower intensity is now attributed to a local fault east of the San Andreas rift, known as the Stanford fault, as well as to the character of the foundation underlaying the plain. The Stanford fault is a branch of the San Andreas fault which had not been recognised in 1906, and was not discovered until 1916. No information on the construction of the dam was found.

10) Pilarcitos Dam. The Pilarcitos earth dam is situated 1.7 miles southwest of the fault line at the southern part of its lake. The dam was built in 1866 and is described by Schussler. The fill material is a light brown clayey sand, probably derived from weathering of the Martinez sandstone formations which form the east valley wall. The properties of the fill material were discussed by Sherard. The foundation material is composed mainly of sandstone shale and limestone. The northeast end of the dam was founded on basalt and Cahil sandstone, Lawson (1914). During the 1906 earthquake the seismic intensity on the dam site was rather low. No damage was reported.

11) San Leandro Dam. The San Leandro dam is a semi-hydraulic fill structure. Schuyler (1901) describes the method employed for the construction of this dam. Nothing, however, is known about the soil properties of the fill and core wall material. The dam is built on tertiary formations of the Leona rhyolite type. By 1906 the reservoir was silted up to a depth of 40 feet. The earthquake did not cause any damage, the intensity of the shock at the site being very low, nevertheless, it produced waves 3 feet high which broke against the dam and passed over the spillway.

12) Piedmont Dam. This earth dam was built in 1905, probably rolled in layers. It has no core-wall and the borrow material was scraped from the floor of the reservoir area. The fill is composed of silty sand, a decomposed product of the Franciscan sandstone formations. The dam is founded on sandstone.

The dam was completed only a few months before the earthquake and had just been filled for the first time. The results of the earthquake were a few transverse and longitudinal cracks near one end of the dam, and a settlement in the centre of about 6 inches. A survey of the dam in 1930 showed a lateral deflection of the crest of 6 inches downstream and at the same time, it was estimated that the upstream concrete facing had settled 18 inches at crest level.

13) Temescal Dam. The Temescal dam is a semi-hydraulic fill structure similar to the San Leandro dam. It was built in 1869 to a height of 100 feet and subsequently hydraulic fill was used to raise it to the present height of 105

feet. Nothing is known of the properties of the fill material. The dam is founded on rock.

A rather severe earthquake, associated with ground rupture and probably with fault displacements along the Hayward fault, occurred in October 21, 1868. At the time the dam was incomplete, and the fault passing in the vicinity of the dam seems quite certain to have shaken the structure considerably. No statement, however, has been found that the dam at that stage of construction was damaged. Following the 1906 earthquake no serious effect was reported, except a number of minor cracks which developed near the crest of the dam.

II) IMPERIAL VALLEY EARTHQUAKE, June 22, 1915

Epicentre 32 48N, 115 30W, Magnitude ? , Intensity IX RF.

14) Volcano Lake Dyke. The Volcano Lake dyke is situated about 25 miles south of Calexico, Mexico. No account of the construction of this dyke was found. It was probably built up gradually over a number of years between 1890 and 1900 impounding the waters of the Volcano Lake. By 1915 the lake had been silted up to a depth ranging from 4 to 10 feet over an area of 20 square miles. The Volcano Lake area is composed of very soft saturated deposits and is notorious for its seismic activity. During earthquakes, columns of mud are often seen rising from vents of mud-volcanoes which are numerous in the area. The Imperial Valley earthquake of June 22, 1915 was especially severe at and about Volcano Lake and the dyke was demolished. The shock was described by some people as being strong, but Mexicans living at the east end of the lake described the shock as very slight. It was not possible to obtain consistent information concerning the intensity of the shock at the site. It appears, however, that the intensity of the shock did not exceed VI + RF. The structure was inspected immediately after the earthquake and it was found to be completely destroyed with apparent spreading and fracturing of the main body of the dyke. No cracks were found on the dry ground adjacent to the dyke; and where the structure cracked, the fill was damp. Cracks 18 inches wide running along both upstream and downstream slopes were found to extend 5 feet into the body of the dyke. In many places the structure had opened. On November 20, 1915 a second shock occurred which, however, was much less intense. After these earthquakes the dyke was reconstructed to be demolished again by the Imperial Valley earthquake of 1940. The fault line crossed the structure at right angles through its centre. No details of the damage were given except the fact that the dyke broke at more than six points flooding the area downstream. The intensity of the shock at this point is not known, but it probably was at least IX MM.

III) TEJON PASS EARTHQUAKE, October 22, 1916.

15) Fairmont Dam. The construction practice and foundation conditions are described by Kelly (1916). Although it is known that the Fairmont dam was subjected to moderate shocks during the Tejon Pass and Santa Monica earthquakes and that it has settled near the left abutment, no details are available on its actual behaviour. The owner of the dam does not consider that this structure had suffered any damage in the past.

IV) KWANTO EARTHQUAKE, September 1, 1923

Epicentre 35 25N, 139 50E, Magnitude 8.3, Intensity X RF.

16) Ono Dam. The Ono earth dam was built in 1912 for the Tokyo Electric Light Co., forming part of the Yatsuzawa Hydroelectric Power Scheme. It is situated on the river Katsura in the Yamanashi Prefecture. Structural details and soil properties of the fill are given by Kambara (1933). The embankment and core wall material were well compacted and seepage was prevented by two puddled clay core walls. The right abutment rests directly on the Palaeozoic rocks but the rest of the dam rests on the conglomerates and diluvial deposits of the Ono terrace which have a maximum thickness of about 35 feet at the left abutment. Although the diluvial deposits of volcanic origin near the surface were removed, some of the upper layers of gravel were left in place.

During the Kwanto earthquake the water level of the reservoir was 19 feet below the crest of the dam. Although the epicentral distance was over 60 miles, the seismic intensity on the site, on firm ground, was estimated to be nearly 0.15g, while on soft ground the intensity was almost 0.30g. No reliable information is available on the most probable value of the seismic intensity at Ono; it appears, however, that it did not exceed 0.15g.

The result of the earthquake was to fracture the dam in many places. The crest of the structure settled nearly a foot and many fissures 100 to 180 feet long, varying in width from 2 to 10 inches were found to extend to a depth of 35 feet below the surface of the dam. However, one fissure separating the fill material from the core wall was found to extend 70 feet below the crest, Shibusawa (1925). Two local slides about 60 feet long developed on the downstream face of the dam. It is reported that after the earthquake the dam was repaired and the fissures were filled with a mixture of clay and sand.

In 1934, the shear wave velocities in the body of the fill were measured and it was found that near the crest the velocities were only 52 m/sec compared with 88 m/sec 50 feet below the crest. This difference has been attributed to the fracturing in the upper portion of the dam.

17) Lower Murayama Dam. This earth dam belongs to the Tokyo Metropolitan Water Works Bureau and accounts of its construction and soil properties are given by Kambara (1933). The structure itself is a rolled fill with puddle clay core. The construction methods and soil properties of the dam were very similar to those of the Ono and Upper Murayama dams. The dam is founded on stiff tertiary formations of clayey sand overlain by dense gravel.

As a result of the Kwanto earthquake, whose intensity on the site did not exceed 0.12g, the dam settled bodily by 8 inches and longitudinal cracks were formed near the crest. The water level at the time was 30 feet below the crest and the concrete facing blocks on the upstream slope sunk irregularly about 7 inches. The concrete break-water at the crest was completely demolished and the downstream slope of the structure showed a tendency to move outwards. On the downstream berm, which settled 4 feet, cracks 5 inches wide and about 60 feet long were developed. The part of the dam below the berm moved 6 feet downstream and was raised by 2 feet. The ditch at the downstream toe was distorted into an arched shape over a length of 540 feet. At the point of maximum movement the ditch was raised by 2 feet and displaced downstream by 6 feet. In general a spreading tendency of the fill was observed.

Seismic surveys on the dam carried out in 1934 showed that the shear wave velocities near the crest were about 114 m/sec while 50 feet below the crest the velocities were 121 m/sec.

18) Upper Murayama Dam. This structure is founded on tertiary formations overlain by a dense sandy-gravel bed containing in places lenses of soft clay, 5 to 10 feet thick. The clay beds were stripped off in most of the foundation area except near the upstream edge of the dam where a layer of clay 170 feet long and 6 feet thick was allowed to remain.

During the 1923 earthquake the structure was still under construction half of its total height having been completed. The seismic intensity on the site was estimated to have been about 0.12g, and it is noteworthy that a crack, over an inch wide, 225 feet long and 33 feet deep was formed near the upstream edge of the partly finished embankment. Extensive fissures half an inch wide and extending down into the fill over 12 feet formed a zone of fracture about 8 feet wide. This fracture zone extended to a considerable distance along the dam at a distance of about 82 feet upstream of the centre. Undoubtedly this fracturing of the body of the dam was due to the presence of the clay lense whose low strength allowed spreading of the fill.

The dam was completed in 1927. Shear wave velocities measurements of the fill showed values of 105 and 99 m/sec respectively at the crest and 50 feet below the crest. The increase in shear wave velocities near the crest was attributed to the fact that the crest had been used as a causeway and that local compaction of the surface material had taken place.

19) Tokyo Embankments. The damage inflicted on the embankments of the rivers in the Tokyo area amounted to 9% of their total length. It appears that instances of damage were most numerous in those parts of the embankments where the predominant oscillations were at right angles to the axis. Overall sliding or bulging at the toe of the embankments occurred over 19% of the total length which failed. Local sliding between the crest and a horizontal section at 1/3 of the embankment height accounted for a further 26%, while slides occurring between 1/3 and 2/3 of the embankment height involved 43% of the damaged length.

V) SANTA BARBARA EARTHQUAKE, June 29, 1925.

Epicentre 34 18N, 119 48W, Magnitude 6.3, Intensity IX RF.

20) Sheffield Dam. The Sheffield dam was situated 1.5 miles north of Santa Barbara, California. It was built of pit-run material from the reservoir excavation, compacted by passing construction equipment over the fill. The upstream slope was protected by a clay blanket 4 feet thick which was carried 10 feet into the foundation to serve as a cut-off. This clay blanket was protected by a facing of articulated concrete slabs 20 x 20 feet in plan, 5 inches in thickness. According to Nunn (1925), every precaution was taken to insure safe construction.

The dam-site is underlain by a stratum of Eocene sandstone which dips slightly in the downstream direction. The surface material, however, is a bed of bouldery alluvium with a horizontal surface. It consists in general of well rounded large boulders of Eocene sandstone in a matrix of sand, sandstone pebbles and small boulders, and shale pebbles and boulders. The shale material is decomposed and gives some plastic properties to the matrix. The alluvium of this deposit is well compacted and bonded and contains no open spaces. The thickness of this deposit is not known, but at the dam site it extends 10 to 20 feet below ground level. Judging from its relation to the topography Buwalda (1936) infers a maximum thickness of some tens of feet below the bottom of the reservoir. Immediately below the dam, however, the alluvium consists of clayey sand interspersed with silty sand layers and thin layers of clay with boulders. This formation extends to a depth of 4 to 22 feet below ground level where the sandstone is encountered.

The outlet pipe passed below the dam at about its midpoint and was laid in a trench later filled with clay puddle. This pipe was connected to a steel gate tower situated 15 feet upstream of the toe.

The dam failed on June 29, 1925 when an earthquake of moderate intensity occurred in the Santa Barbara region. Before 1925 the area of Santa Barbara is known to have been subjected to a number of earthquakes of moderate intensity. From 1917 until the date of its failure the dam was subjected to earthquakes whose intensity can be inferred to have reached the VI degree on the Rossi-Forel scale. The 1925 shock had an intensity of VIII + RF, while in places due to the alluvial nature of the ground an intensity of IX RF was reached. Willis (1925) indicates that in the city of Santa Barbara the intensity probably reached X RF. This is not unreasonable since he was concerned with a district where a swamp and a small river bed had been filled. On the dam site, however, the intensity should have been much less, not exceeding VIII RF. For instance, the steel gate tower of the reservoir did not show any signs of damage, and the San Ysidoro Hotel close to the dam and founded on sandstone, had only a few of its chimneys damaged.

The fact that the dam was built over an active fault and that the structure failed due to the movements of the fault (ENR Jul. 2, p.29, 1925) is incorrect. In addition the information given by Dewell (1925) and Willis* (1925), that the reservoir is intersected by a fault appears to be incorrect. On the map which accompanies Willis's paper a fault termed the South Santa Ynez Fault is shown to pass through the reservoir site; it is not, however, indicated whether the fault was considered active or inactive. The only evidence which Buwalda found in connection with this fault is that the reservoir occupies a depression. A detailed site investigation made by Buwalda in 1936 indicates that the nearest fault to the reservoir, a fault which shows no evidence of being active, is at its nearest point about 1800 feet north of the reservoir. On this point, rather confusing information on the position and activity of this fault is given by O'Shaughnessey (1925) who also states that there was a fault 1.5 miles south of the dam and which he considers to be responsible for the failure of the dam.

Data available from seismograms in 1925 were inadequate to fix the position of the epicentre more exactly than that it was near Santa Barbara. The exact epicentre of the 1925 shock still remains uncertain, but records of aftershocks recorded at Santa Barbara indicate an epicentre about 10 miles west of the city, suggesting association with one of the known faults in the Elwood oil field at the coast.

The failure of the dam released 45 million gallons of water which flooded the lower part of Santa Barbara. There was about 20 feet of water in the reservoir when the earthquake occurred. At the first series of shocks the downstream portion of the central part of the dam moved out as though it were hinged at the left abutment. The great mass of the centre, about 300 feet in length, moved 100 feet downstream and much of the material was washed

*Willis's conclusions regarding the Santa Ynez faults are not concurred in by many geologists, Bull. Seism. Soc. Amer., Vol. 15, p. 147, 251, 255, 279, 282, 302, 305, 308, 320, Vol. 29, p. 235.

out by the escaping water. During its movement the central part of the dam remained practically intact and the plant growth on the downstream side of the displaced mass was later found to be undisturbed. According to Andrews (1925) it appears that the opening of the joints between the concrete slabs of the upstream lining and the cracking of the clay blanket allowed the water to enter the fractured central section of the dam. The pressure of this water in the cracks would have increased the uplift sufficiently to produce failure by horizontal sliding. A somewhat different description of the failure of the dam is given by Nunn who says that the shock had opened vertical fissures from base to top; the water rushing through these fissures carried the dam out in sections. This mode of failure of water retaining earth structures has repeatedly been observed during earthquakes. Oldham (1899) describes the failure of a 10-foot high embankment during the Assam earthquake. The earth-banks retaining the water in a "tank" began to settle, and at one point a transverse crack developed and the two halves of the "tank" separated. Even earth banks near by only 2 feet high were shaken down quite flat. Buwalda (1955) also describes how similar cracks led to the destruction of a small earth dam on the west side of the road between Arvin-Wheeler Ridge. Steinbrugge (1955) shows a picture of this damaged earth dam.

Some people have considered that the failure of the Sheffield dam was due to a flow-slide following the liquefaction of fine sand or silt by the earthquake shock. A special study of the failure was carried out in 1949 by the Corps of Engineers. It was concluded that the failure could not be attributed to a flow slide. The report states that the fact that the portion of the embankment which was displaced remained intact during slide, rules out the possibility of liquefaction of the embankment itself. The fact that the foundation material was well graded and fairly compact, appears to eliminate the possibility of liquefaction in the foundation material. It appears more likely that failure occurred along a shear surface. The factor of safety of the downstream slope reduced to less than 1.00 when an horizontal earthquake acceleration of 10%g was included in the stability analysis.

Another factor which it was thought contributed to the failure of the Sheffield dam was that there has been no stripping of top-soil before construction and that the seepage observed at the toe was a result of water percolating along the porous topsoil.

In concluding, we may mention Richter's (1958) opinion on the matter. ".... Large earthquakes occasionally result in the failure of dams. In the comparatively moderate shaking of the 1925 earthquake at Santa Barbara, an earth fill dam retaining the Sheffield reservoir gave way. Probably this was not different from other effects of intensity VIII MM in soft material."

In August 1925, a temporary earth dam was constructed after removing to bedrock the foundation material. The New Sheffield dam was completed in 1936 by raising the temporary dam of 1925 to a height of 36 feet.

VI) SANTA MONICA BAY EARTHQUAKE, August 30th, 1930.

Epicentre 33°57N, 118°38W, Magnitude Intensity VIII MM

21) Chatsworth Dam. No account of the construction of this dam has been found. It was built in 1918 for the City of Los Angeles. At the time of the earthquake of August 30th, the dam was under repair. In order to decrease the permeability of the dam, loose fill was being dumped on the upstream face while

the water level was drawn down.

As a result of the shock, localised seepage developed through the embankment and a few hours after the shock the flow of water amounted to 8 gallons per minute and it was very turbid. Reports from the area near the dam indicate that glass windows were broken, big chimneys toppled and loose articles were thrown from shelves. The dump fill on the upstream face of the dam slid into the reservoir, and a crack running over the entire length of the crest was opened. Smaller cracks on both upstream and downstream faces of the dam also opened up. The width of these cracks varied from ¼ to 3 inches extending from 5 to 12 feet into the body of the fill.

The maximum intensity of the shock was VIII MM, but on the dam site it did not exceed VI+ MM. This intensity corresponds to that given for the site by Gutenberg (1932) for the regionalisation of the 1930 earthquake, and must have been influenced by surface-ground conditions. The shock was relatively of brief duration and the more violent shaking may have subsided before there was time to produce generally the effects usually characteristic of the intensity experienced. This fact may have contributed in producing a striking anomaly in the regionalisation of the area, namely that an area including a considerable tract of formerly marshy ground was affected by lesser intensity than the immediate surrounding country. Higher rather than lower intensity would naturally be expected in this case. It is said that at the dam site, the Watermaster's car with its brakes set moved 4 feet forwards and then 6 feet backwards shaking the driver from the running board. This event, however is not an indication of severe ground motion. A shock, for instance, barely strong enough to be noticed by an observer standing on the ground will cause plainly visible motion of a car. A parked car is an excellent seismoscope, and its magnification factor is large enough to have its springs broken, as the case is with the car parked on Bear Mountain during the Kern County shocks of 1952. During the earthquake of April 22, 1952 in Montana, a jeep parked at the Dry Creek area with locked wheels moved 3 feet; the intensity of the shock there was only VI MM. Many other similar cases of parked cars and trucks moving distances up to 6 feet with their wheels locked have been observed and associated with intensities not exceeding VII+ MM.

VII) HAWKES BAY EARTHQUAKE, 3-13 February 1931.

Epicentre 39°30S, 177°00E, Magnitude 7.9, Intensity X RF.

22) Hawkes Bay Embankments. Railway and roadway embankments on the epicentral area sunk and spread to such an extent that they were rendered useless. These embankments were composed of dry cohesionless soils and were founded on comparatively sound ground. Fourteen embankments in the Napier area, varying in mean height from 20 to 77 feet with slopes of 1½:1, all settled by about 12% of their height, and their slopes were flattened to $2^1/3$:1 Adjacent to Napier, a long causeway, ranging from 6 to 16 feet in height, across the Ahurri lagoon split wide open along the central line. In some places, the overall width of the embankment increased to more than double its original dimensions. The longitudinal crack extended vertically down to the original mud of the harbour bottom, in some places being over 15 feet wide. At some points, the fill, after spreading, collapsed inwards and the sea water was able to flow into the large crack. At other points the comparatively flat bottom of the harbour, composed of natural gravel deposits overlaying silt, was displaced bodily from a higher to a lower level. Embankments 16 feet high near the Turaekuri bridge flowed towards the river carrying with them the first piers at each end of the bridge, which collapsed a few hours

after the earthquake.

In many instances, silt and silty sand deposits overlain by dense gravel were observed to have liquefied under the earthquake shock, as a result of which cracks appeared in the gravel. The gravel slid on the very gentle bedrock slopes underlying the liquefied material. Fine silts were also ejected into the air through the cracks opened in the gravel and overlaying soil. The loss of strength of sensitive soils was observed in many instances. A heavy monument at McLean Park sank over 5 feet into the ground but after the earthquake it was found to be undamaged and in an upright position; chimneys and open fire-places dropped below floor level, and heavy machinery on block foundations sunk as much as 2 feet without sustaining any serious damage.

VIII) PERU EARTHQUAKE, October 10th, 1938.

23) Malpasso Dam. This rock-fill dam is founded on a 100-foot thick glacial drift consisting of boulders mixed with gravel sand and silt. A concrete cut-off wall 26 feet thick extending in some places 140 feet down to bedrock, was placed on the upstream toe of the structure and was connected with an apron to the upstream 2-foot thick concrete revetment of the structure. A very thin monolithic concrete diaphragm, 3 to 5 feet thick was placed in the central plane of the dam. The upstream slope of the dam is very steep, built by hand and derrick laid boulders the voids of which were filled with fine sluiced material.

In 1938, with the reservoir full, the structure was subjected to a slight earthquake, as a result of which its crest moved 2 inches downstream and settled about 3 inches. Although the intensity of the shock at the site was not accurately determined, from information collected it appears that it did not exceed VI+ MM. In November 10, 1946, the structure was probably shaken again, but no data concerning damage are available.

IX) IMPERIAL VALLEY EARTHQUAKE, May 18th, 1940.

Epicentre $32^{\circ}46$N, $115^{\circ}28$W, Magnitude 7.1, Intensity X MM.

24) Laguna Dam. No information on the construction method and soil properties of this earth dam have been found. The structure is built on horizontally stratified stiff shale containing sandstone seams. The abutments of the dam are founded on strong sandstone. The seismic intensity at the damsite was only VI+ MM, but the damage to railroad embankments and levees on soft ground near the damsite was rather severe. Nothing is known about any damage to the dam.

25) Imperial Valley Canals. At the time of the 1940 earthquake the All-American canal was nearly completed but no water had yet been admitted. As a result of the shock the earth banks of the canal were badly shattered; large stepwise lurchings and slumping down into the excavation was observed. The embankments were intersected and offset by the fault trace; the north-south offset on the northern embankments amounted 4 feet 10 inches.

Damage to other irrigation canals was widespread and serious. Breaks occurred over almost the entire length of the Ash Canal. At least one bank of the Solfatara Cana' was destroyed over a length of 13 miles, and 4 miles of embankments of the East Side High Line Canal collapsed. In Mexico, the embankments of the Central and Alamo Canals were broken over a length of 25 miles. In all, about 60 miles of canal embankments were damaged or destroyed. The intensity in those areas was high, in places over IX MM.

On December 4th, 1948, an earthquake shock of intensity as low as VI MM, opened one old crack in the Coachella branch of the All-American Canal. On July 29th, 1950, a strong shock of an intensity of VIII MM occurred and irrigation ditch banks and embankments sloughed and the ground settled and cracked along the Vail Canal. The August 1st shock of the same year produced additional damage to the Vail embankments. On January 23rd, 1951, the canal embankments near Trifolium cracked and settled. On December 5th, 1951, a VII MM shock caused cracks and damage in the canal embankments 10 miles northeast of Brawley. On June 13th, 1953 the Thistle Canal, south of Westmorland was damaged, and half a mile of canal embankment was cracked. One of the canal regulating structures collapsed.

X) EARTHQUAKE of June 4th, 1940.

Epicentre 33°07N, 116°25W, Magnitude Intensity V MM.

26) Moreno Dam. This rock-fill dam belongs to the City of San Diego Californ: In 1940 it is known to have been subjected to a slight shock, but no damage has been reported.

XI) CENTRAL CHILE EARTHQUAKE, April 6-7th, 1943.

Epicentre 30°45S, 72°00W, Magnitude 8.3, Intensity X RF.

27) Cogoti Dam. The Cogoti dam is one of eighteen rock-fill dams built in Chile during the early 1930's. These dams are the earliest structures of their type designed empirically with special reference to earthquake resistant properties. Information on the construction of the Cogoti dam is given in the Engineering News Record, Vol. 107, p. 725, of 1931. The dimensions and properties of the fill were arrived at by a study of rock slides in the district which is known to be seismic. A laminated concrete paving was used for facing the upstream slope of the dam and this served as the sole impervious element of the structure.

As a result of the 1943 earthquake which, on the dam site had an intensity of IX RF, the structure settled 15 inches. According to information supplied to the author, the damage to the structure was insignificant. Rock slides, however, developed on the downstream slope, and rocks rolled downstream.

XII) EARTHQUAKE of November 13th, 1943.

Epicentre 38°12N, 119°00W, Magnitude Intensity

28) Bridgeport Dam. This earth dam was built in 1924 and no reliable record of its construction has been found. It is in Mono County, California, and in 1943 it was subjected to a slight shock, but no damage has been reported.

XIII) UZBEKISTAN EARTHQUAKE, 1944.

29) Boz'suiskaya Dam. This earth dam was built in Uzbekistan, USSR, by dumping the fill material into water at temperatures as low as $-5^{o}C$. While the dam was under construction, considerable blasting was carried out in the vicinity. Two years after completion a strong earthquake occurred as a result of which the structure settled about 11 inches. No other defects were revealed. It is believed that the intensity of the shock did not exceed VII MM.

XIV) MANIX EARTHQUAKE, April 10th, 1947.

Epicentre 34°58N, 116°32W, Magnitude 6.4, Intensity VII MM.

30) Summit Dam. Nothing has been found about Summit dam except that it was badly cracked by the earthquake shock. The intensity of the earthquake at the site was VII- MM. A small reservoir dug in the ground near-by was not affected but water was thrown over its banks.

XV) MONTANA EARTHQUAKE, November 23rd, 1947.

Epicentre 44°47N, 112°02W, Magnitude Intensity VIII MM

31) Ruby Dam. The Ruby dam is situated across the Ruby Valley near Alder, Montana. The intensity of the shock at the dam site was VIII MM, and there seemed to be severe ground movements which detached boulders from the 300 feet high rock cliffs. Some of these boulders landed close to the reservoir. No damage was reported. The Holter dam, near Wolf Creek was shaken at the same time, but the intensity at the site was only VI MM, but again no damage was reported. The Hebgen dam, near Greyling was also shaken with the same intensity, but no damage was sustained by the structure.

XVI) FUKUI EARTHQUAKE, June 28th, 1948.

Epicentre 36°08N, 136°17E, Magnitude 7.3, Intensity XI MM.

32) Hosorogi Embankment. The Hosorogi embankment was constructed across a valley 1660 feet wide just north of the Hosorogi Station near Kitagata-mura, Fukui. It carried the Morita-Hokuriku railway line and had a maximum height of 28 feet. The embankment was constructed of silty clay and the same material was used for the construction of the rest of the Hokuriku embankment extending between Sabae and Iburi-bashi, a distance of 31 miles. The embankment was founded on soft alluvium and borings show that bedrock lies more than 160 feet below the ground surface. From seismic refraction investigations it appears that even at depth of 1330 feet no indication of bedrock appears. The surface deposits in the basin are soft organic silts and it appears that much of this material has been used for the construction of the embankments.

The embankments collapsed completely. The intensity of the shock was computed for the site and was found to be as high as 45%g. The embankment in most places slumped to 40% of its original height while it was displaced horizontally by as much as its full width. Cross-sections of the embankment after the earthquake show that it was first broken into blocks by the shock and the unequal subsidence of its foundation, and it was then flattened to a shapeless mass of earth blocks. The foundations sunk considerably and rows of rice plant on both sides of the embankment were heaved up and compressed at the toes of the slopes. In many places the structure flowed out leaving the tracks in the air. At other points the track was turned upside down by the flow of the fill material, which in places moved 50 feet from its original position. The type of failure generally observed along the Hosorogi embankment indicates clearly a base failure and spreading of the fill; the fundamental cause being the soft foundation material. The fact that the collapse was due to base failure is best illustrated by the evidence that houses built on soft ground near Kitagata-mura sunk more than 3 feet into the ground but sustained absolutely no damage to the roof and structural members.

XVII) CALIPATRIA EARTHQUAKE, July 29th, 1950.

Epicentre 33°O&N, 115°34W, Magnitude 5.5, Intensity VIII MM.

33) North End Dam. Nothing has been found about this dam except that it is in the vicinity of the Vail Canal near Calipatria. The earthquake shock at the site was rather strong and old sheet piling on the spillway broke as the dam settled. The ground near the downstream toe cracked and near-by irrigation ditch embankments sloughed. In Auguwt 1st of the same year, a light shock of VI MM shook the dam again and ground fissures opened wider in the vicinity of the structure.

XVIII) GRAN SASSO EARTHQUAKE, September 5th, 1950.

Epicentre 42°31N, 13°20E, Magnitude 5.5, Intensity VIII MM

34) Poggio Cancelli Dam. This earth dam is in the province of Abruzzo, about 60 miles northeast of Rome, Italy. It was built between 1941 and 1943, but it did not function as a water retaining structure until 1950-51. The fill material is sandy silt, and the same material with the addition of 3% bentonite was used for the construction of the core of the dam. It is founded on a rather thin layer of sandy clay interspersed with silt pockets. The bedrock is about 20 feet below ground level and it consists of sandstone.

The Gran Sasso earthquake was rather severe, and its epicentre was very close to a known fault (Amatrice-Gransasso), the shock being associated with a superficial movement of this fault. The shock near the dam site was less intense than that observed a few miles northeast of the site, this anomaly being attributed to the nature of the overburden. This anomaly, however, is in accordance with Baratta's Chart of Seismicity in which the dam site is shown to be on a slightly seismic region. The epicentral distance of the dam was onlt 4 miles, and the shock intensity there was VII MM. No statement has been found on the extent to which the dam was damaged.

Another earth dam, the Arvo dam (built in 1931, 115 feet high) in the province of Cosenza is reported to have been shaken during the last twenty years by a number of moderate earthquakes, but no damage resulted. The maximum intensity experienced by this dam did not exceed VI+ MM.

A number of other earth dams in Italy have also been subjected in the east to slight shocks, but none of them sustained any damage. These dams are the Bomba dam in the province of Chieti, the Osento dam in Avellino, the San Biagio dam (built in 1958, 113 feet high) in Frosinone and the Castel San Vincenzo dam (built in 1957, 94 feet high) in Combobasso. The Bomba dam is situated in a highly seismic region; the rest of the dams are in regions of moderate seismicity.

XIX) CALIFORNIA-NEVADA EARTHQUAKE 1951.

35) Yuba Dam. This dam belongs to the Nevada Irrigation Distributors, and is situated 5 miles east of Nevada City, California. No account of the construction has been found. The dam was built in 1909 and was raised in 1949. The foundation material is composed of a thick layer of sandy residual clay. It is reported by Sherard (1953) that in the first week of January 1951 a slide occurred on the downstream slope of the dam. On the morning of the slide an employee of the Irrigation District had visited the dam. As he was leaving the area, he felt an earthquake shock and returned to the dam to find a slide 75 feet wide at the midheight of the slope and 60 feet wide at the downstream edge of the crest. The shock was felt in the near-by town and was strong enough to produce a rather extensive slide of a natural hillside which blocked one of the main canal arteries of the irrigation system. Seismic records for the first week of January 1951, however, do not indicate such activity at the vicinity of the Yuba dam. It may be conjectured that the probable dates of the event should be one of the following: 11th or 12th November 1950 - felt in Carson City; 14th November 1950 - rather strong, felt in Northern California-Nevada; 16th November 1950 - rather slight; 14th December or 13th January - moderate; 22nd January 1951 - 75 miles away from the dam site, rather strong (VI MM); 25th January 1951 - 110 miles from the dam site (VI+ MM).

XX) ARVIN-TEHACHAPI EARTHQUAKE, July 21st, 1952.

Epicentre 35°00N, 119°02W, Magnitude 7.7, Intensity X MM*

36) Bouquet Dam. This dam is owned by the City of Los Angeles. It is of rolled fill construction built in 1932-3 under strict laboratory control. It has been stated that there was no damage to this structure.

37) Buena Vista Dam. This earth structure retains the waters of the Buena Vista Lake into which Kern River drains. This dam was built on very soft alluvium and according to analyses made in the past, gypsum is being leached from this alluvium. The crest of the dam carries on its southern half a railroad track while a road is located on its northern half. Since the construction of the dam in 1890, it has been enlarged, its slopes protected by rip-rap and in many instances repaired, as in 1907 when the dam was breached. Leaks developed at other times and in 1927 a puddle core extending through the dam section was added. The core was placed where layers of gypsum were known to exist near the downstream toe of the fill. In 1938 leakage was again observed and a part of the structure was strengthened with additional material.

The region where the dam is built is known to have been repeatedly

* Urban area intensities did not exceed VIII MM.

subjected to comparatively strong earthquakes. During the earthquake of October 22nd, 1916, water waves 10 inches high were excited in the reservoir, and during the 1951 earthquake water waves 5-foot high were developed.

The 1952 earthquake caused considerable damage to this structure as well as to certain parts of the Kern Island Canal, where slumping and fissuring were prominent. Along a length of 200 feet of the west portion of the dam, a settlement of over 2 feet was measured while over a length of 75 feet the settlement amounted 2½ feet and an incipient slide area was revealed. The height of the structure at this point was only 8 feet. A continuous crack was found to run along the crest of the dam for over 2000 feet located between the railroad track and the upstream slope of the structure. In many placew the track subsided 6 to 8 inches and moved horizontally.

At about the time of the earthquake of August 22nd, 1952 (Epicentre 35°20N, 118°55W, Intensity VIII MM), a new leak was noted near the south end of the dam. The structure subsided on both upstream and downstream sides, the available freeboard before the shock being about 5 feet. It was thought that the part that subsided is the portion which was breached in 1907. In general the damage inflicted by the 1952 shocks was aggravated by the solution of the gypsum beds underlying the foundation. It seems likely that some of the cracks and settlement in the fill could have been caused by settlement into the cavities which were created by the solution of the gypsum beds.

38) Dry Canyon Dam. This structure is a semi-hydraulic fill dam built in 1912 for the Los Angeles Aqueduct. Construction methods and fill properties are given by Kelly (1916). The depth of recent alluvium under the dam is about 75 feet and the cutoff wall extends 10 feet into the sandstone bedrock. The abutments and foundation under the overburden consist of thinly bedded soft sandstones and shales. In 1930 slight seepage was observed but was remedied and no further trouble was experienced.

The seismic intensity of the 1952 earthquake, which at the site was V+ or VI MM, produced several cracks running parallel to the axis of the dam along the entire crest and located approximately 5 feet from the downstream edge of the crest. These cracks had a maximum width of 2 inches and were found to extend a depth of 16 feet down to the hydraulic fill core. An incipient slide towards the lake displaced the fill by about 4 inches, while cracking occurred over the downstream third of the crest width. This movement also caused bulging of the concrete facing and parapet wall on the upstream slope. The dam settled nearly 3 inches and results from check surveys of the structure showed a horizontal displacement of about 2½ inches towards the reservoir.

The dam has been repaired by sealing the cracks and by flattening the cross section. The required flattening was calculated by adding 10%g and assuming that the dam was on the verge of failure at the time of the earthquake

39) Isabella Dam. No account of the construction methods and the earthquake resistant design were made available. It appears, however, that the dam is built partly on solid rock and partly on decomposed rock. Depending on the foundation conditions, horizontal seismic forces equal to 10% or 5% of the weight of the structure were used in the stability analysis. The required factor of safety was then reduced. It appears that the dam was under construction when the 1952 earthquake occurred.

Another earth dam, 100 feet high, across the Kern River was also nearly completed at that time. This dam founded on weathered granite and built of compacted decomposed granite was 7 miles northeast of Hobo Hot Springs and about 52 miles from the epicentre.

Nothing was made available on the seismic behaviour of these dams.

40) South Haiwee Dam. This is a semi-hydraulic fill structure built in 1913 for the Los Angeles Aqueduct. Construction data are given by Kelly (1916). The upper half of the west abutment consists of recent alluvium while the lower half, underlying the alluvial material, consists of a lake bed material resembling siltstone. This siltstone extends almost to the base of the east abutment which is of rhyolithic flow rock. The recent alluvium under the dam has a maximum thickness of 125 feet. A puddle core was taken down to the siltstone.

The dam site has often been subjected to strong earthquakes. In March 1872 movement on the Siera Nevada fault caused an earthquake between Owens Lake and the town of Bishop, and movement on other parallel faults south of the lake. Fissures were opened from Haiwee to a point north of Big Pine, a distance of 70 miles. In places the ground settled from 2 to 30 feet, ponds were formed and drainage lines were changed. There was also a tidal wave on Owens Lake. This was probably due to the fact that the east shore of the lake was slightly elevated and the west side was depressed by about 2 feet.

On February 9th, 1917, it appears that the dam should have been subjected to a slight shock. On the same year the dam was shaken again with an intensity VII+ RF. This shock caused a break 160 feet long in the concrete flume of the Los Angeles Aqueduct at a point near Haiwee. No damage to the dam was reported. On August 19th, 1922, a strong earthquake occurred and as a result the Aqueduct was broken near Haiwee and two hundred feet of railway track were washed out.

The dam is 96 miles from the epicentre of the earthquake of July 21st, 1952. No damage of any sort was reported by the caretaker of the dam. The intensity of the shock was only VI MM. However, an inspection of the structure after the shock, revealed the presence of numerous cracks about 6 feet deep along a 700 foot section of the crest where the dam has its maximum height. In some places the width of the cracks amounted to over 1 inch but in general the cracks were about ¼" wide. These cracks were located near the upstream edge of the crest. The cracking formed an arcuate pattern starting at the upstream edge and extending across the crest and on to the downstream slope. Fissures also appeared running parallel to the face of the dam adjacent to the rip-rap. The general pattern of cracking indicated that a slide was about to start but had not moved more than a few inches. A series of levels run on the crest of the dam two weeks after the shock showed a settlement of the crest of 1 inch.

Repair work, including strengthening and modification of the existing cross section has been carried out to assure stability of the dam. The shear strength of the fill material used to calculate the amount of flattening required was obtained by assuming the dam was on the point of failure without seismic forces. A 10% seismic acceleration acting horizontally was then applied and the new cross section was required to have a factor of safety of one for this seismic condition.

41) Tejon Ranch Dam. This dam is known to have been shaken more severely in

1952 than any of the other dams. No precise information concerning its seismic behaviour was found, but it appears that no damage was caused.

42) Name not known (II). An unindentified private earth dam, 11 miles to the north-east of the epicentre, and 3 miles from the White Wolf Fault was completely destroyed. The shaking at this region of the San Joaquin Valley was especially severe.

Damage to small private reservoirs in the area was also reported. Longitudinal cracks opened up in the embankments and settlement and slumping occurred on the upstream side. In some cases where the reservoirs were full of water the embankments gradually slumped and filled the reservoirs. It was found that the amount of damage varied with degree of saturation of the foundation materials. The U.S. Coast and Geodetic Survey reported that earth reservoirs in the central area were flattened, but no details were given.

43) Tinemaha Dam. This earth dam belongs to the City of Los Angeles. No account of the construction of this structure has been found. The maximum intensity of the 1952 shock at the dam site was only V MM and no damage has been reported.

44) Long Valley Dam. This earth dam was built in 1940 and no reliable record of its construction has been found. It belongs to the Los Angeles Aqueduct and is situated north of Bishop, California. The seismic intensity at the dam site was VI- MM, and no damage to the structure has been reported.

45) Deer Creek Dam. The seismic intensity at the dam site was VII MM, and according to press reports the structure cracked and settled. It is also reported by the U.S.C.G.S. that this earth dam - on the Los Angeles Aqueduct - cracked.

46) Davis Dam. This is a U.S.B.R. dam of the Davis-Parker Project in the Arizona-Nevada area. Construction methods and fill properties are given in the U.S.B.R. Publication "Development of earth dam design in the Bureau of Reclamation" August 1958. The seismic intensity was very low (IV MM) and no damage has been reported.

XXI) FALLON EARTHQUAKE, July 6th and August 23rd, 1954.

Epicentre	39°25N,	118°32W	Magnitude	6.6	Intensity	IX MM
"	39°35N,	118°27W	"	6.8	"	IX MM

47) Lahontan Dam. A detailed account of the construction of the Lahontan dam is given by Tillinghast (1913). The foundation material consists of seamy broken sandstone, mudstone and shale of varying degree of hardness. The overburden, composed of sandy clay and gravel, was removed and the dam was built on mudstone and stiff clay.

The seismic activities of July 6th and 7th, and August 23rd of the Fallon-Stillwater region were the strongest on record in the area. The Lahontan dam site is at an epicentral distance of about 30 miles and the structure is built on strong foundation materials. Preliminary reports of the seismic effects on the structure made available indicate that the dam was not damaged. It appears that this dam also withstood a shock of comparable intensity during the earthquake of December 20th 1932.

The damage caused to other structures in the Fallon-Stillwater area by the 1954 earthquakes was mainly due to poor foundation conditions and the intensity of VIII+ to IX MM is probably of a local nature. Extensive damage was caused to canal and drainage facilities of the Newlands Project. Culverts collapsed and longitudinal cracking and sloughing occurred in many places along both drainage channels and irrigation canal embankments. Canal levees settled from 1 to 3 feet and the bottoms of canals were raised by 1 to 2 feet. In one case the bottom of a drainage ditch was raised by 6 feet. The seismic intensity in this area was VIII MM. At the Wildlife Area the East Canal was severely damaged for about 2 miles and 200 yards were completely destroyed. West of Fallon a 40-foot portion of an embankment, about 20 high, failed completely although the intensity was only VII MM.

48) Coleman Dam. This is a composite concrete-earth diversion structure and it is located one mile northwest of Fallon. Reports indicate that the structure was destroyed during the earthquake. This structure failed because of displacement and cracking of the earth-fill abutments, which in turn permitted water to erode around the concrete portion, causing it to partially overturn, crack and settle. The earth abutments were completely washed out. No information about the foundation and fill material has been found.

49) Saguspe Dam. This is a diversion earth-fill structure. Nothing authoritative was learnt about its seismic behaviour except that it settled over a foot. The shock of August 23 opened up a crack in the dam which subsequently failed.

50) Rogers Dam. This dam was reported to have failed during the earthquake of August 23rd in Fallon. No details were found but it appears that the structure, like Coleman dam, was composed of a central concrete spillway with two earth-fill embankments. It was situated 3 miles northeast of Lovelock in Nevada. The southeast part of the dam composed of earth fill gave way and a portion of the concrete structure was broken off and turned around into the stilling basin.

An unindentified earth-fill crossing the river east of Tule Ranch - southeast of Lovelock - also failed.

XXI) EUREKA EARTHQUAKE, December 21st, 1954.

Epicentre 40°49N, 124°05W, Magnitude 6.6, Intensity VII MM

51) Arcata Dam. This earth dam was built in 1936 across the Jolly Giant Creek. The upstream part of the structure is impervious while the downstream fill is composed of coarse pervious material. The structure is founded on solid rock. The seismic intensity at the site was very small and according to information the structure was not damaged. There were, however, breaks in the draw off pipes.

52) Eureka Dam. This structure consists of an excavation between two embankments. The embankments were constructed of earth removed from the excavation. The reservoir is divided into two compartments by a reinforced concrete wall. The interior surface of the fill is lined with concrete reinforced with steel mesh. The reservoir was leaking prior to the earthquake, and after the shock the leakage increased to 1.7 million gallons per day. As a result of the shock, the concrete lining broke near the toe drains and it appears that this fracture was caused by the settlement of the fill.

XXII) SAN FRANCISCO BAY EAST EARTHQUAKE, October 23rd, 1955.

Epicentre 37°58N, 122°03W, Magnitude 5.4, Intensity VII MM.

53) Saint Mary's Dam. Structural details of this earth dam have not been found. Following the shock of October 23rd and its aftershocks the dam was inspected for damage. It was found that a crack 3 inches wide had developed along the upstream face of the dam. This crack was continuous from the right end of the dam to the spillway and again from the spillway to the left end of the dam. Subsequently pits were excavated along the crack and it was found that the crack was directly above the concrete core wall which was 4 feet below the crest. Near the centre of the dam where the height of the core wall is the greatest, it was found that the wall had undergone a displacement downstream of about 2 inches. At the junction of the core wall and the spillway structure, no displacement of the core was found. It was thought that the rigidity of the concrete core wall was directly responsible for the crack. The structure was repaired by harrowing the fill over the wall so that the existing crack was filled.

XXIII) TBILISI AND TADZHIKSKAN EARTHQUAKES, 1957.

54) Kairakkumskaya Dam. This dam is a hydraulic fill structure made of fine grained sand. It was constructed in 1955-57 and forms a part of the Kairakkumskoy Hydroelectric Project in Tadzikskay, USSR. The dam was designed to withstand seismic accelerations of the order of 10%g. Full details of the stability and structural analysis of the project is given by Maslov (1958). Since the completion of the structure, the site has been shaken by earthquakes of intensity not exceeding VI MM. No damage has been reported.

55) Minguechaurskaya Dam. This hydraulic fill structure was built across the river Kura in Caucasus near Tiflis, of coarse grained sand and loam. The design of the dam was based on the "Dynamic filtration theory" developed by Maslov (1954, 1955), and extensive description of the large model tests and of the theory used is given in the Nauchnie Trudi (1954). The dam was designed to withstand a seismic acceleration of 5%g. The foundation material consists of 165 feet of sandy loam which overlies bedrock. During the years following the completion of this structure, the site has been shaken by numerous rather slight earthquakes of intensity not exceeding VI- MM, but no damage has been reported.

XXIV) EARTHQUAKE of March 18th, 1957.

56) Cachuma Dam. This is a U.S.B.R. earth dam built in California in 1950-53 Design features are given in the U.S.B.R. "Development of earth dams" (1958). It was built on a 70 feet thick layer of alluvial formation overlying shale and siltstone. This structure is mentioned here since it is the first earth dam for which seismic records of its motion during earthquakes have been obtained. U.S. coast and Geodetic Survey type accelerographs were installed on the crest of the dam and in the valve house at the downstream toe. The accelerographs recorded the shock of March 18th (Magnitude 4.7) and show that the ground acceleration (1%g) was magnified at the crest of the dam to 2½%g.

XXV) MEXICAN EARTHQUAKE, July 28th 1957.

Epicentre 17°00N, 99°00W, Magnitude 7.5 Intensity

57) Pinzanes Dam. This is a rock-fill dam described by Tercero (1959). It is founded on rock and reinforced concrete slabs form an impervious diaphragm on the upstream slope of the structure.

This dam was not damaged by the July earthquake, but the intensity at the dam site was only 5%g.

XXVI) HEBGEN LAKE EARTHQUAKE, August 17th, 1959.

Epicentre 44°50N, 111°05W, Magnitude 7.1, Intensity X MM

58) Hebgen Dam. At the time of writing this paper no authentic information on the extent of damage was available. It would appear, however, that the shock at the site did not exceed VIII MM. While the preliminary reports of the U.S.C.G.S. cites only the intensity of the main shock in the grade IX category, the relative light damage to structures in the epicentral area hardly supports a grade VIII evaluation. From the examination of photographs of the dam after the shocks it is tentatively suggested that, an intensity of only VII+ was experienced at the site. The caretaker's house on the right abutment of the dam was undamaged, telephone poles on the dam were only slightly distorted and the telephone wires sagged. The more prominent surface faulting associated with the earthquake occurred north and northeast of Hebgen Lake. One zone of scarps can be followed for six miles a short distance above the dam; the height of these scarps is about 15 feet.

The whole crustal formation of the lake underwent severe tilting and shorelines emerged by as much as 8 feet in the southern part of the lake. The shorelines in the northwest part were submerged by several feet. This tilting created water waves 3 feet high which overtopped the dam.

As a result of the shock the earth fill settled five feet on both sides of the central concrete core wall and several cracks, from 2 to 6 inches wide were opened in the concrete core wall. The fill on both sides of the core cracked and slumped. Although the full extent of the damage cannot at this time be ascertained, preliminary reports indicate that the dam suffered considerable damage, including cracking and settling of the concrete spillway and rather alarming leakage occurred after the shocks.

Bibliography

1. - Andrews R. (1925) "Report of Committee on buildings for safety against earthquakes" Bull. Seism. Soc. Amer., Vol. 15, p. 201

2. - Buwalda J. (1936) "Geological conditions affecting safety of Sheffield dam and reservoir near Santa Barbara, California" Unpublished Report, January 7, 1936, City of Santa Barbara.

3. - Buwalda J. (1955) "Earthquakes in Kern County during 1952" Bull. Dapt. Natur. Resources, Division of Mines, Nr. 171, p.43

4. - Corps of Engineers U.S. Army (1949) "Report on the investigation of failure of Sheffield dam and reservoir near Santa Barbara, California" Unpublished Report, June 1949, City of Santa Barbara, California.

5. - Dewell H. (1925) "Earthquake damage to Santa Barbara buildings" Eng. News Record, Vol. 95, pp 68, 149.

6. - Gutenberg B. et al. (1932) "The earthquake in Santa Monica Bay, California on August 30, 1930" Bull. Seism. Soc. Amer., Vol. 22 p. 138.

7. - Harza L. (1951) "Rock-fill dams" 4th Intern. Cong. Large Dams, Rep. 20, p. 162

8. - Henny D. (1932) "Dams on the San Andreas fault" Eng. News Record Vol. 109, p. 385.

9. - Kambara S. et al. (1933) "Study of physical laws governing infiltration of water through the dam and its subjacent soil" 1st Congr. Large Dams, Vol. 4, p. 119.

10. - Kelly A. (1916) "Complete report on the construction of the Los Angeles aqueduct" Dept. Public Service, City of Los Angeles.

11. - Lawson A. (1914) "San Francisco Folio" Dept. Interior, U.S.C.& G.S. Nr. 193

12. - Maslov N. (1954) "Uslovia dinamicheskoy ustoychivosti vodonasischenjih peskov" Nauki Trudi, Voprosi Mehaniki Gruntov, Nr. 18, Leningrad.

13. - Maslov N. (1955) "Uslovia ustoychivosti sklonov i otkossov v'gidroenergeticheskom stroytelstve" Moskow.

14. - Maslov N. (1958) "Voprosi mehaniki gruntov" Sbornik Trudov, Nr. 28, Leningrad.

15. - Nunn H. (1925) "Municipal problems of Santa Barbara" Bull. Seism. Soc. Amer., Vol. 15, p. 311.

16. - Richter C. (1958) "Elementary Seismology" Freeman Press.

17. - O'Shaughnessey M. (1925) "Sheffield and Gem Lake failures" Eng. News Record, Vol. 95, p. 194.

18. - Schussler H. (1906) "The water supply of San Francisco etc." Martin B. Brown, N.Y.

19. - Schuyler J. (1901) "Reservoir for irrigation, water power and domestic water supply" Wiley, pp. 77, 294.

20. - Sherard J. (1953) "Influence of soil properties and construction methods on the performance of homogeneous earth dams" U.S. Bureau of Reclamation, Tech. Memo. 645.

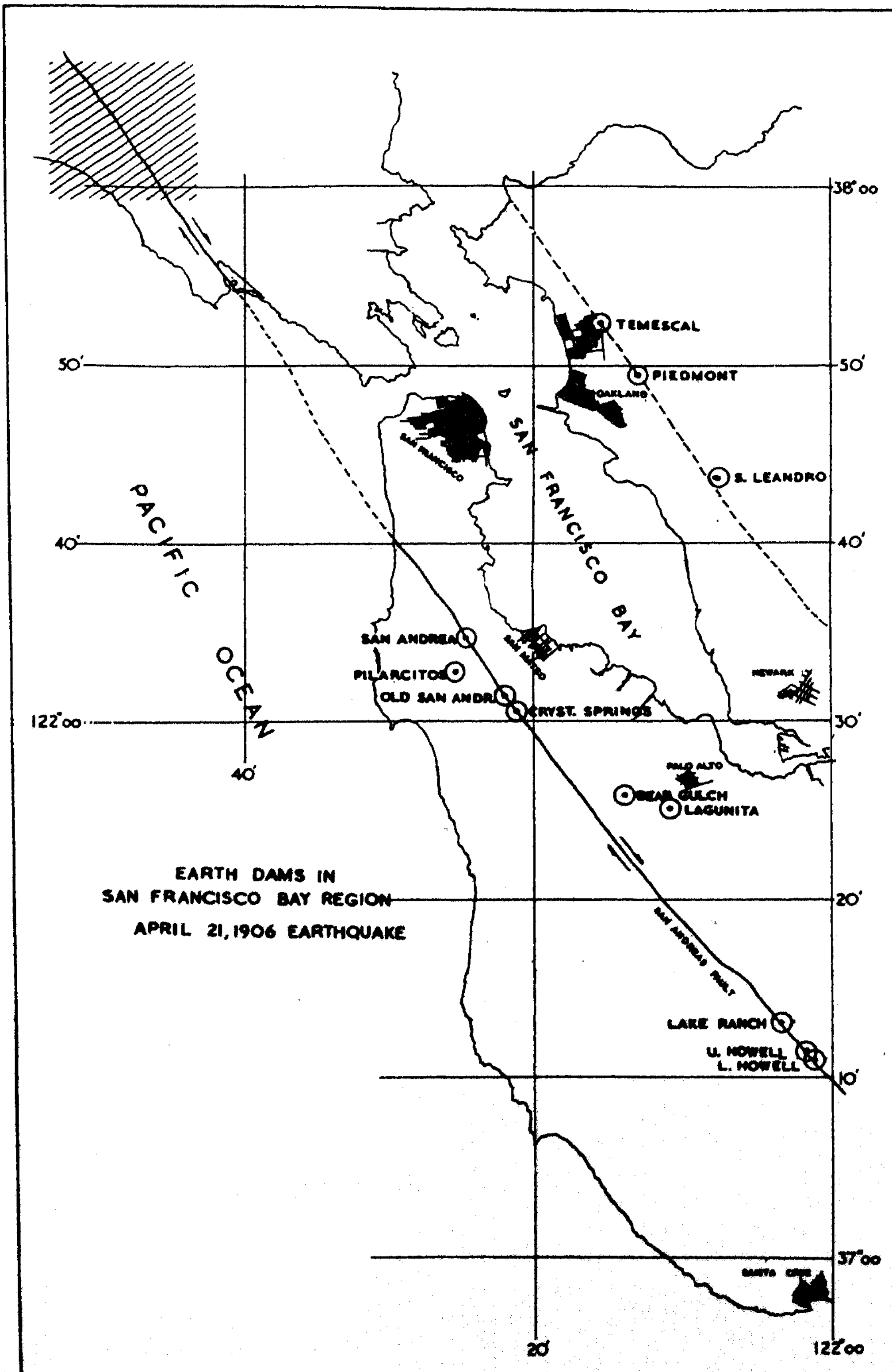
21. - Shibusawa M. (1925) "A description of the damage done by the great earthquake of September 1st, 1923 to the electrical installations in Japan" Intern. Congr. Large Transm. Systems, Vol. 2, p. 9, Paris

22. - Steinbrugge K., et al (1955) "Earthquakes in Kern County during 1952" Bull. Dept. Natur. Resources, Division of Mines, Nr. 171, p. 258.

23. - Tercero C. (1959) "Rock-fill dams" Journ. Power Div., Proc. Amer. Soc. Civil Eng., Vol. 85, Nr. PO2, p. 51

24. - Tillinghast F. (1913) "The Lahontan Dam" Eng. & Contr., Vol. 39, p. 189

25. - Willis B. (1925) "A study of the Santa Barbara earthquake of June 29, 1925" Bull. Seism. Soc. Amer., Vol. 15, p. 255.



38°00
50'
40'
122°00
40'
30'
20'
10'
37°00
20'
122°00
TEMESCAL
PIEDMONT
OAKLAND
S. LEANDRO
SAN FRANCISCO BAY
PACIFIC OCEAN
SAN FRANCISCO
SAN ANDREA
PILARCITOS
OLD SAN ANDR.
CRYST. SPRINGS
SAN MATEO
NEWARK
PALO ALTO
BEAR GULCH
LAGUNITA
SAN ANDREAS FAULT
LAKE RANCH
U. HOWELL
L. HOWELL
SANTA CRUZ
EARTH DAMS IN
SAN FRANCISCO BAY REGION
APRIL 21, 1906 EARTHQUAKE

STATISTICAL DATA OF DEFECTS AND FAILURES IN EARTH DAMS DUE TO SEISMIC ACTIVITY

Name of Dam	Country	Year of Constr	Type	Hght (ft)	Length (ft)	Crest (ft)	Upstr. Slope+	Downstr. Slope+	Imperv. Element§	Found. Condit.*	Age	Epicent. Distnc. (mils)	Seism. Intensity# G	Accel. P	Damage^	Name of Dam
1.- SAN ANDREAS	USA	1870	E	95	890	25	3.5	3	C(0)e	D(40)R	36	0	X RF	25%	C	SAN ANDREAS 1
2.- UPPER CRYST. SPRINGS	USA	1878	E	75	700	31	2;3¼	2(75)3½	C(0)e	D(60)DD	28	0	X RF	25%	C; Sh	UPPER CRYSTAL SPRINGS 2
3.- OLD SAN ANDREAS	USA		E	23	180				-	DD		0	X RF	25%	Sh	OLD SAN ANDREAS 3
4.- LAKE RANCH	USA	1877	E	38	160	20	2.75	2½	-		29	0	X RF	25%	ND	LAKE RANCH 4
5.- UPPER HOWELL	USA	1878	E	36	630	20	2	2	-		28	0	IX RF	20%	C;S	UPPER HOWELL 5
6.- LOWER HOWELL	USA	1877	E	38	480	18	2	2½	-		29	0	IX RF	20%	B	LOWER HOWELL 6
7.- Name not known (I)	USA		E+C									2	VIII RF	15%	F	Name not known (I) 7
8.- BEAR GULCH	USA	1896	E	45	730	27	3	3	-	DD	10	2	VIII RF	12%	ND	BEAR GULCH 8
9.- LAGUNITA	USA	1900	E	15	2500	7	3	3	-		6	4	IX RF	20%	ND	LAGUNITA 9
10.- PILARCITOS	USA	1866	E	95	520	25	2;2½	2	C(o.10)e	D(45)R	40	2	VIII RF	10%	ND	PILARCITOS 10
11.- SAN LEANDRO	USA	1876	E+H	125	500	28	3;4	7	-	R	30	19	VII RF	7%	ND	SAN LEANDRO 11
12.- PIEDMONT	USA	1905	E	51	250	15	2	2	-	R	1	19	VII RF	5%	C;S	PIEDMONT 12
13.- TEMESCAL	USA	1868	E+H	105		18	3	5	-	DD	38	18	VII RF	7%	ND	TEMESCAL 13
14.- VOLCANO LAKE	Mexico		E	12		20	2	4	-	AA	15	23	VI+ RF	5%	F	VOLCANO LAKE 14
15.- FAIRMONT	USA	1912	sH	121	4300	16	3	2	C(0)c	R	4			4%	ND	FAIRMONT 15
16.- ONO	Japan	1912	E	124	1080	24	2½(8)3	2(9)2½(9)2½(9)3	C(o.12)e	D(30)R	11	60	IX RF	15%	CC;S	ONO 16
17.- UPPER MURAYAMA	Japan	1923	E	80	1060	21	3	2(5)2½;30;4	C(o.10)e	A(10)R	1	86	VIII RF	12%	CC;S	UPPER MURAYAMA 17
18.- LOWER MURAYAMA	Japan	1927	E	101	1930	24	3	2(9)30;4	C(o.10)e	A(20)D	-4	87	VIII RF	12%	C	LOWER MURAYAMA 18
19.- Tokyo Embankments	Japan	-	E	-	-	-			-	A			X RF	25%	F	Tokyo Embankments 19
20.- SHEFFIELD	USA	1917	E	30	800	20	2½	2½	URec	D(10)DD	8	11	VII+RF	10%	F	SHEFFIELD 20
21.- CHATSWORTH	USA	1918	E	44	2700	21	2½	2½	-		12	12	VII RF	6%	C;IS	CHATSWORTH 21
22.- Hawkes Bay Embankments	N.Z	-	E	-	-	-	1½	1½	-	D(40)A			X RF	20%	F	Hawkes Bay Embankments 22
23.- MALPASSO	Peru	1936	R	255	500	22	½	1⅓;1½	URc;C(0)c	D(100)R	2		VI MM	4%	ND	MALPASSO 23
24.- LAGUNA	USA	1938	E	50	580	10	2½	2½		R	2	42	VI MM	4%		LAGUNA 24
25.- Imperial Val. Canals	USA	-	E	-	-	-				A			IX MM		F	Imperial Val. Canals 25
26.- MORENO	USA	1896	R	165	550	20					44		IV MM	2%	ND	MORENO 26
27.- COGOTI	Chile	1938	R	275	520		1.6	1.8	URc	R	5		IX RF	14%	S	COGOTI 27
28.- BRIDGEPORT	USA	1924	E	70	780	15					19			3%	ND	BRIDGEPORT 28
29.- BOZ'SUISKAYA	USSR	1943	E	90	920		3;3.75;4½	4;4½	-	D	2		VII MM	7%	ND	BOZ'SUISKAYA 29
30.- SUMMIT	USA		E									8	VII MM	8%	CC	SUMMIT 30
31.- RUBY	USA												VIII MM	12%		RUBY 31
32.- Hosorogi Embankment	Japan		E	28	1670	18	1½	1½	-	AA		3	XI MM	45%	F	Hosorogi Embankment 32
33.- NORTH END	USA		E										VII MM	8%	C;S	NORTH END 33
34.- POGGIO CANCELLI	Italy	1943	E	56	1500	10	2½	2;2½	C(1/20)e	D(20)R	7	4	VII MM	7%	ND	POGGIO CANCELLI 34
35.- YUBA	USA	1910	E	28	880	12	2½	1.75	-	D	41		VI MM	4%	S;Sl	YUBA 35
36.- BOUQUET	USA	1934	E	190	1190	50	3	3	-	DD	18	50	VII MM	7%	ND	BOUQUET 36
37.- BUENA VISTA	USA	1890	E	17	33000	20	3;4	3;4	D(0)e	AA	62	17	IX MM	25%	S;CC;IS	BUENA VISTA 37
38.- DRY CANYON	USA	1912	sH	67	550	20	2½	2.3	-	A(75)R	40	46	VI MM	5%	S;IS;C	DRY CANYON 38
39.- ISABELLA	USA	1953	E	185	1650	20				R		54	VI MM	4%		ISABELLA 39
40.- SOUTH HAIWEE	USA	1913	sH	91	1550	20	2½	2½	-	A(115)D	39	98	VI MM	5%	S;IS;C	SOUTH HAIWEE 40
41.- TEJON RANCH	USA	1946	E	32	580	12					6	11	X MM	25%	ND	TEJON RANCH 41
42.- Name not known (II)	USA		E				3½	2(12)2¼	-	A		10	IX MM	25%	F	Name not known (II) 42
43.- TINEMAHA	USA	1928	E	32	5800	43	2½	2(10)2	S(2)(1.4)e	D	24	61	V MM	3%	ND	TINEMAHA 43
44.- LONG VALLEY	USA	1940	E	126	600	30	+				12		VI MM	4%	ND	LONG VALLEY 44
45.- DEER CREEK	USA		E										VII MM	7%	C	DEER CREEK 45
46.- DAVIS	USA	1950	E+R	138	1600	50	3						IV MM	2%	ND	DAVIS 46
47.- LAHONTAN	USA	1915	E	125	1700	20	3	2(12)2	S(3)(1.1)e	D	39	31	VI MM	3%	ND	LAHONTAN 47
48.- COLEMAN	USA		E+C									16	VII MM	8%	F	COLEMAN 48
49.- SAGUSPE	USA		E							D		13	VII MM	8%	F	SAGUSPE 49
50.- ROGERS	USA		E+C									35	VII MM	7%	F	ROGERS 50
51.- ARCATA	USA	1937	E	55	160	17	2	2½	U(2)(o6)e	R	17	5	VII MM	8%	ND	ARCATA 51
52.- EUREKA	USA		E									5	VII MM	8%	ND	EUREKA 52
53.- SAINT MARY	USA	1928	E	55	285	20	2½	2	C(0)c	A	27		VII MM	7%	C;S	SAINT MARY 53
54.- KAIRAKKUMSKAYA	USSR	1957	H	117	4500	25	2½;3;3½;4	2;3½;4½	C(o.20)e	DD	1		VI MM	4%	ND	KAIRAKKUMSKAYA 54
55.- MINGUECHAURSKAYA	USSR	1957	H	271	3800	53	2½;3⅓;5	2⅓;3½;4;5	C(o.25)c	A(165)D	1		VI MM	4%	ND	MINGUECHAURSKAYA 55
56.- CACHUMA	USA	1953	E+R	275	2980	40	3(25)4	2;2½;6(20)5	C(1.68)(o.5)e	A(70)D	4			1%	ND	CACHUMA 56
57.- PINZANES	Mexico	1956	R	180	820	17	1/5	1/3	URc	R	1		VI MM	4%	ND	PINZANES 57
58.- HEBGEN	USA	1913	E	87	720	20	3	2.6	C(o.1)c	DD	46	0	VII+MM	10%	CC;S	HEBGEN 58

E = Earth dam
R = Rock-fill
H = Hydraulic (sH = Semi-hydr.
C = Concrete (gravity-type)

+ Figure in brackets indicates dimensions in Ft. of berm between successive slopes. § C=central core, S=sloping core, UR=Upstream revetm. e=compacted earth, c=concrete, (m)= batter in m:l. * AA=very soft alluv., A=alluvium, D=Diluvial formations, DD=Soft rock, R=Rock, ( )=thickness of superficial stratum.

Seismic intensity refers to the damsite. Seismic acceleration deduced from microregionalization effects on the site.
^ Damage: F=failure, CC=seriously cracked, B=breached, Sh=sheared, S=settled, IS=incipient slide, ND=not damaged, Sl=slide.

DISCUSSION

G. R. Oca, National Power Corporation, Philippines:

This is a follow-up of my first comment. The San Andreas Dam and the Upper Crystal Springs Dam had withstood the San Francisco earthquake of 1906. I wish to call attention that both dams were founded on rock. On the other hand, San Francisco City, 50 or so miles away from the fault was damaged considerably. You will note that the poorer condition of the subsoil in San Francisco clearly demonstrates the effects of earthquakes on structures. Hence it may be advanced that foundation conditions have very significant bearing with respect to the resonance of buildings or other structures considering other controlling factors to be equal or similar.

N. N. Ambraseys:

Dr. Oca has called attention to the effect of the foundation conditions on damage of earth dams.

There is usually a decrease in intensity as the distance from the fault or epicentre increases, but other conditions may exert a strong controlling influence, and changes in distance from the seat of disturbance do not influence the gradiation in intensity so much as do changes in the character of the ground. Other things being equal, I agree, that the amount of damage produced by an earthquake at some distance from its epicentre depends chiefly upon the nature of the ground.

The immediate vicinity of a fault-break, however, may not show maximum destructive effects on structures. This may be true to some extent with uniform superficial geology; possibly, according to Louderback, because of the incomplete development of surface waves right at the seat of disturbance. In any case, regardless of the foundation conditions this is conspicuously true when variations in near-surface geology do exist and the intensity may not be exceptionally high as measured by elastic wave vibration in the vicinity, especially when the fault-break reaches the surface (San Francisco 1906, Cocopah 1940, Dixie Valley 1954, Hebgen 1959 etc.)

However, I would say that the effect of the foundations on damage of structures cannot be treated independently of the type of structures standing on them. The foundation-superstructure system is a unity, acts as such and must be examined as such during an earthquake. In many instances, in the vicinity of a fault-break rigid structures founded on comparatively soft ground fared much better than similar structures built on rock. At some distance from a fault-break the opposite effects have been observed. (loc. Atlas of the Report, Investig. Commt. San Francisco Earthquake 1906 Nrs. 9, 10, 11, 12 13, 14, 20, 22, 26, 27, 28, 29 and 40 Map Nr. 22)

Finally, I would like to point out that neither the San Andreas nor the Crystal Springs dams are founded on rock; both are on gravelly alluvium. As to what extent the earthquake of 1906 tested the ability of these earth dams to retain water is rather difficult to say. From the evidence available on the 1906 earthquake it appears that no dramatic situation was created on the dam sites.

M. Hatanaka. Kobe University, Japan:

In case of earthquake, shearing strength of soils, that is internal angle of repose adhesion, pore-pressure etcs. seem to be different from those under normal state.

I would like to have some information if available, since I have been conducting a fundamental experiment on the shearing strength of soil during vibration.

N. N. Ambraseys:

I am unfortunately unable to answer in a few minutes Dr. ~~Hatanaka~~ Hatanaka's inquiry about the seismic behaviour of soils. The limited number of experimental results seems to show that the seismic behaviour of soils is certainly different from their static behaviour.