Observed Performance of Concrete Dams during Earthquakes

1. General Performance of Concrete Dams

Perhaps hundreds or more concrete dams have been shaken by earthquakes felt at or near the dam site, but only about 20 have experienced recorded or estimated peak ground accelerations (PGAs) of 0.20g or higher. The most severely shaken dams include all principal types of concrete structures: gravity, arch, and buttress.

Earthquake shaking alone has never caused failure of a concrete dam. The failure of the Shih Kang concrete gravity dam in the 1999 Chi-Chi earthquake in Taiwan was the result of direct fault displacement of about 9m under the dam.

2 Gravity Dams

2.1 General

In the epicentral area of the earthquake, a number of concrete gravity dams have experienced ground shaking in the order of 0.4g PGA or higher without apparent damage.

Koyna Dam in India suffered relatively significant damage in an earthquake in 1967. It is a 105m high concrete gravity dam, and was subject to 0.63g PGA. Because of the significance of the performance of this dam in relation to the proposed dam at Mokihinui, it is considered further in Section 2.2. Other concrete gravity dams subject to earthquake loading are summarised in Section 2.3.

2.2 Koyna Dam

Koyna Dam (India) was constructed during the years of 1954 and 1963. It is a straight concrete gravity dam, 105m high and 850m long, constructed in 15m wide blocks. The spillway portion of the dam is about 90m long (Figure 1).

The non-overflow and overflow (spillway) sections of the dam are shown in Figure 2. The cross-section of the non-overflow blocks is not typical of gravity dams (Figure 3). Departure from a typical section was the result of changes in design that were introduced while construction was in progress, because it was decided to combine the originally planned two stages of construction into one.

A major earthquake (M6.5) occurred in 1967, with the epicentre within 15km of the dam. The peak horizontal accelerations recorded by the accelerograph located in a gallery of Block 1A (refer Figure 1) were 0.63g in the longitudinal (cross-valley) direction and 0.49g in the transverse (upstream-downstream) direction. The other accelerograph in Block 13 failed to function.

The most important structural damage to the dam was horizontal cracks on the upstream and downstream faces of the higher non-overflow blocks (Blocks 13 to 18, and Blocks 25 to 30, Fig 1). On the downstream face of these blocks, an approximately horizontal crack developed at the level where the slope of the downstream face changes abruptly (level KRL 2060 of Figure 2). Horizontal cracks were also observed on the upstream face of these blocks, especially near KRL 2060.

No cracking was found on the spillway dam blocks.

There was evidence of relative movement between adjacent blocks: spalling of concrete along the vertical joints between adjacent blocks, and a considerable increase in seepage through the contraction joints between adjacent blocks after the earthquake, especially from between Blocks18 and 19 and also Blocks 26 and 27.

Cores drilled from the foundation gallery into the foundation rock through the concrete indicate that the contact between rock and concrete had not been suffered any distress. No important changes in the uplift pressures seemed to have been caused by the earthquake.

The dam did not appear to be in danger of failure immediately following the event, but the damage was serious enough to result in lowering of the reservoir for inspection and repairs. The cracks were repaired by injecting epoxy resin and the taller non-overflow monoliths were prestressed over the height from roadway level to a depth of 20m below the major cracks.

In view of the increase in seismic activity in the vicinity of Koyna Dam and the weakening of the dam by the 1967 earthquake, it was considered necessary to strengthen the entire dam. The non-overflow monoliths were strengthened by increasing the section over the entire width of the monolith from the base up to KRL 1970 (refer Figure 2), and providing buttresses above this level.

2.3 Other Concrete Gravity Dams

Shih-Kang Dam (Taiwan) was severely shaken during the Chi-Chi earthquake in 1999. It is a gravity dam, about 25m high, and has about 18 gated bays that serve as a spillway. The dam was directly intersected by fault rupture, with a differential movement of about 9m vertical and 2m horizontal under bays 16 to 18. The fault had not been mapped at the site prior to the earthquake. Bays not affected by the fault rupture survived essentially undamaged. A PGA of 0.56g was recorded in a town nearby.

Mingtan Dam (Taiwan) is a 82m high concrete gravity dam, which was subject to peak accelerations of 0.30g to 0.50g during the 1999 Chi-Chi earthquake. The dam experienced no damage. Pressure relief wells in the foundation experienced an increased in head, but were re-drilled and uplift pressures went back to normal.

Lower Crystal Springs Dam (California) is a 39m high curved concrete gravity dam which withstood the 1906 San Francisco Earthquake (M8.3, estimated) without a single crack. The rupture trace of the San Andreas Fault was less that 150m from the dam. Searville Dam, another 20m high gravity arch dam constructed near the San Andreas Fault, also performed satisfactorily in 1906.

2.2 Arch Dams

No significant damage has ever been suffered by an arch dam in an earthquake. More than 40 arch dams in 14 countries are known to have been subject to significant earthquake shaking. Only five have experienced peak ground accelerations greater than about 0.3g. These five are Pacoima and Gibraltar dams in California, Ambiesta Dam in Italy, Techi Dam in Taiwan, and Rapel Dam in Chile. Except for Pacoima Dam, which suffered damage during two recent earthquakes, all of the other 40 or so dams experienced very little or no damage. Other arch dams have been subject to significant ground motion from earthquakes with their epicentre located several tens of kilometres from the dam site.

Pacoima Dam is a 113m high medium-thick arch dam of moderate double curvature. The centre of the dam is 30m thick at its base and 3m at the crest. It has a crest length of 195m and was constructed in 1929. The dam has been subject to significant shaking from two major earthquakes during its working life. The first was the 1971 San Fernando (M6.7) earthquake, and the second the 1994 Northridge (M6.7) earthquake. Although severely shaken in both events, with peak ground accelerations in the range of 0.55g to 0.8g, Pacoima Dam survived the earthquakes. There was no noticeable cracking of the dam in 1971, but in 1994 there were some visible cracks and block offsets. Repairs included the strengthening of the left abutment area with stressed anchors. Reanalysis indicates that the rehabilitated dam should perform satisfactorily if subject to the maximum credible earthquake for the site, and the dam is still in service.

Techi Dam (Taiwan) is a 180m high double curvature arch dam with a crest length of 290m and constructed in 1973. It was subject to significant ground shaking from the 1999 Chi-Chi earthquake (M7.6) with the lake at its near-full level. The dam is located 85km from the epicentre of the earthquake. The PGA at the site was estimated at between 0.3g and 0.5g. No damage to the dam concrete was observed. There were no signs of vertical joint movements. Collected seepage increased in the days following the earthquake, but returned to normal.

Ambiesta Dam (Italy) is a 65m high arch dam built in 1956. In 1976 it was subject to 0.33g PGA shaking from a M6.5 earthquake 20km away. The dam did not suffer any damage from this event.

Rapel Dam (Chile) is a 110m high double curvature arch dam. The crest length is 270m and the thickness of the arch varies from 19m at the base to 5.5m at the crest. The dam was subject to shaking from a M7.8 earthquake centred 45km from the dam site. Freefield instruments located near the dam recorded a PGA of 0.31g. It was noted however, that the peak horizontal acceleration occurred in a direction more or less parallel to the dam axis. The upstream-downstream component, theoretically more critical to the dam, was only 0.14g. The arch dam performed satisfactorily in this event.

Gibraltar Dam (California) is a 52m high arch dam built in 1920. It was not damaged in the 1925 M6.3 Santa Barbara earthquake which occurred beneath the dam.

2.3 Buttress Dams

The most significant example of a buttress dam subjected to severe earthquake shaking is the Sefid Rud Dam in Iran. It is a 106m high and was extensively cracked in the region about 15m below crest level when subject to 0.7g PGA shaking. Severe leakage occurred, but the dam did not fail catastrophically. It was repaired and is still in service.

3 Concrete Dam Design for Earthquakes

Prior to the mid 1970s, typical practice was to design dams for nominal earthquake forces only (generally 0.1g to 0.2g). Nevertheless, as outlined above, such dams have survived earthquake loads that may have been five to ten times greater than considered in design. This performance record demonstrates the inherent earthquake resistance of well proportioned and well built concrete dams.

Current dam safety criteria require that the safety of existing dams, not specifically designed for very high earthquake loads, be evaluated for extreme earthquake loads likely at that site. Large existing dams in New Zealand have commonly been reassessed for earthquake loads having a 1 in 10,000 year recurrence interval. For example, Aviemore Dam on the Waitaki River was analysed for a PGA of 1.07g and was found to generally meet modern dam safety criteria. The only upgrade required was to the spillway gates and the associated spillway bridge structure.

Large RCC dams greater than 80m high have been built in recent years, or are being planned or under construction. Several of these are located in areas of high seismic activity and have been designed for earthquake loads greater than 0.5g. Examples include the 97m high Olivenhain Dam in California, the 103m high raise of San Vicente Dam in California, the 95m high Platanovryssi Dam in Greece, the 78m high Jahgin Dam in Iran, the 84m high Ghatgar Dam in India and several dams in China up to 217m high.

4 Performance of Dams in the 2008 Wenchuan Earthquake

The May 2008 Wenchuan earthquake in the Sichuan Province of China had a moment magnitude M_W of 7.9. The south-western area of China in which Sichuan Province is located is the most important hydropower energy base of China. Many hydropower projects have been constructed or are under construction in this area.

Initial reports indicate that 1583 dams and reservoirs were damaged (some significantly) by the earthquake. Most of the dams were subject to peak ground accelerations much greater than their design value. Yet no dams failed during or after the earthquake.

Main damage comprised:

- Cracks and leakage,
- Crest settlement and slope movement on embankment dams, and
- Failure of water discharge and power generation facilities.

A major RCC dam is located 12km from the epicentre. This is Shapai Dam, which is a 132m high RCC gravity arch dam designed for a PGA of 0.14g. No reports are available yet on its condition because it has not been accessible. A helicopter inspection has shown that the dam is basically in a safe condition.

Another major dam located 17km from the epicentre is the 156m high Zipingu concrete-faced rockfill dam, completed in 2006. More initial information is known about this structure than Shapai Dam. The measured acceleration at the dam crest was 2.0g, indicating that the PGA at the dam foundation may have been in the range of 0.5g to 1.0g (ground motions are amplified up the height of a dam). Also, the maximum measured crest settlement was 730mm, which is equivalent to about 0.5% of the dam height. This result is again indicative of a PGA at the site in the order of about 0.5g to 1.0g. Damage included cracks at the dam crest and distortion of the upstream facing slab. The powerhouse and associated buildings at Shapai have apparently collapsed and the whole generation installation is out of commission. The reservoir is being lowered.

The information available from the Zipingu rockfill dam indicates that the peak ground acceleration at the Shapai RCC dam site would also probably have been in the range of 0.5g to 1.0g.

5 Conclusions

The performance of concrete dams that have been subject to earthquake loading attests to their natural strength reserve. Damage from seismic shaking up to about 0.8g peak ground acceleration has been limited mainly to cracking of the dam wall. Such damage has not threatened the uncontrolled release of water from the reservoir. Significantly, sliding in the rock foundation or in the body of the dams does not appear to have occurred in the recorded events.

Those dams built before modern earthquake design began in the 1970s, and which have survived earthquake loads that may have been five to ten times greater than considered in their design, shows that well proportioned concrete dams are inherently seismic-resistant structures. Analysis of other concrete dams located in high seismic zones for extremely high seismic loads indicates that they will generally meet modern dam safety criteria.

The cracking that occurred on the non-overflow blocks of Koyna Dam, when the dam was subject to about 0.5g upstream-downstream shaking, can be attributed to its unusual sectional profile. In contrast, the overflow dam blocks did not suffer any significant damage. The proposed Mokihiui dam will have a similar section geometry to the Koyna overflow blocks, indicating that its seismic performance will be satisfactory.

Large RCC dams greater than 80m high have been built in recent years, or are being planned or under construction. Several of these are located in areas of high seismic activity and have been designed for earthquake loads greater than 0.5g.

More than one thousand dams survived significant ground motions in the recent earthquake in China without any reported breaching failure. This included a 132m high RCC dam located 12km from the epicentre of the M7.9 event. Because of its location, the dam would probably have been subject to 0.5g to 1.0g ground accelerations. The dam remains in a safe condition, although there are no detailed reports yet on the damage that it may have suffered.

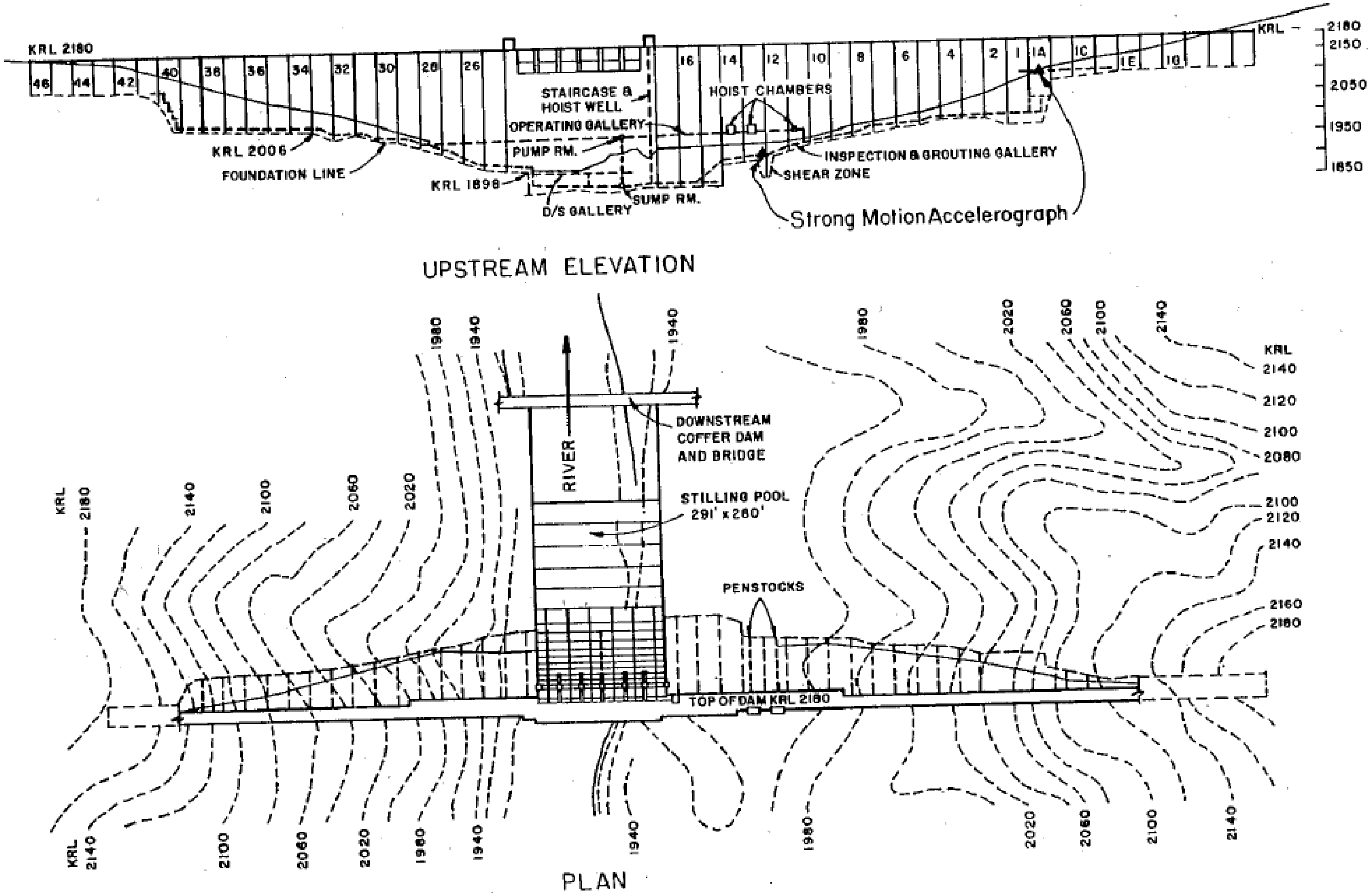

Figure 1: Koyna Dam – Plan and Elevation

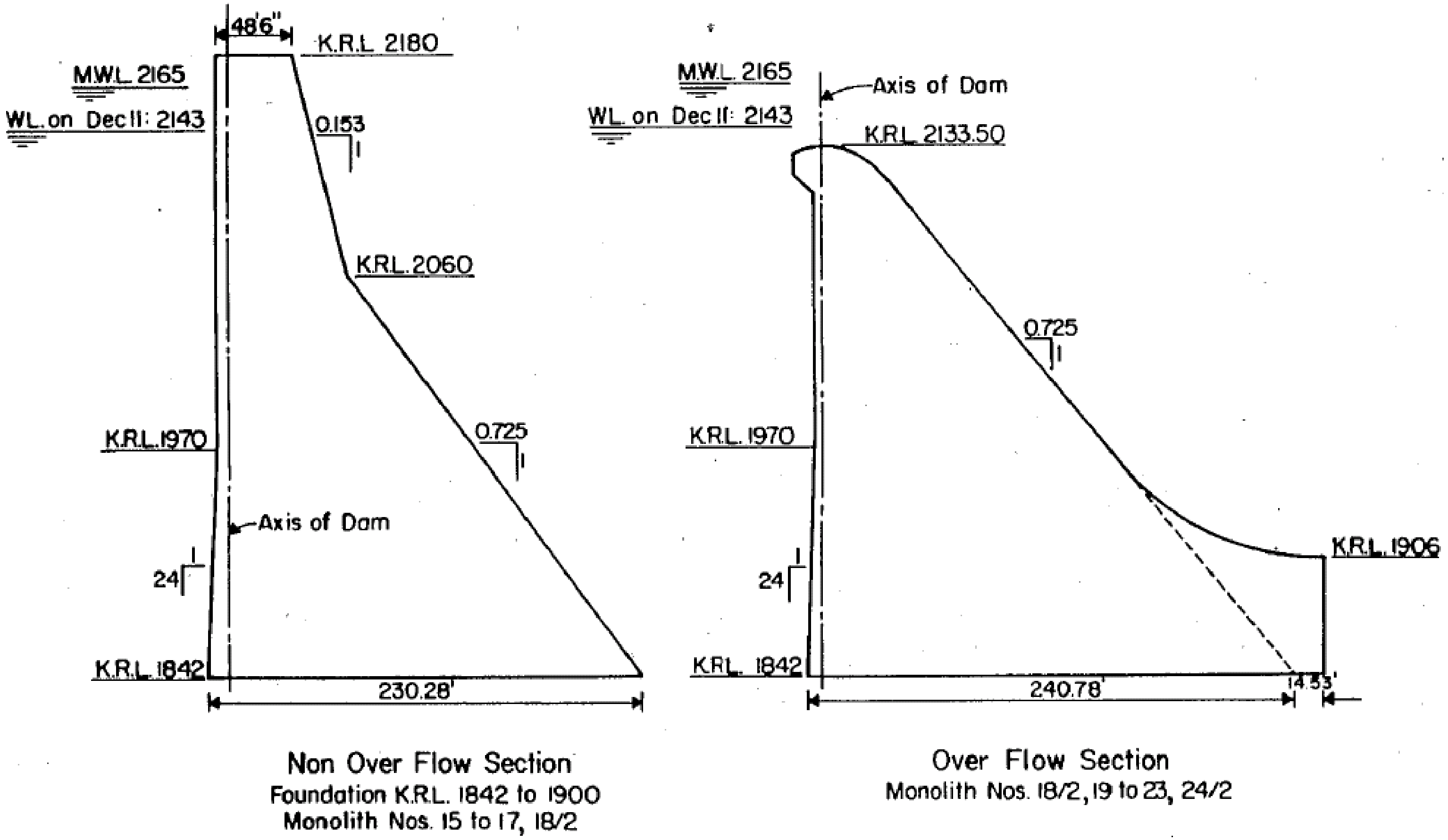

Figure 2: Koyna Dam - Sections

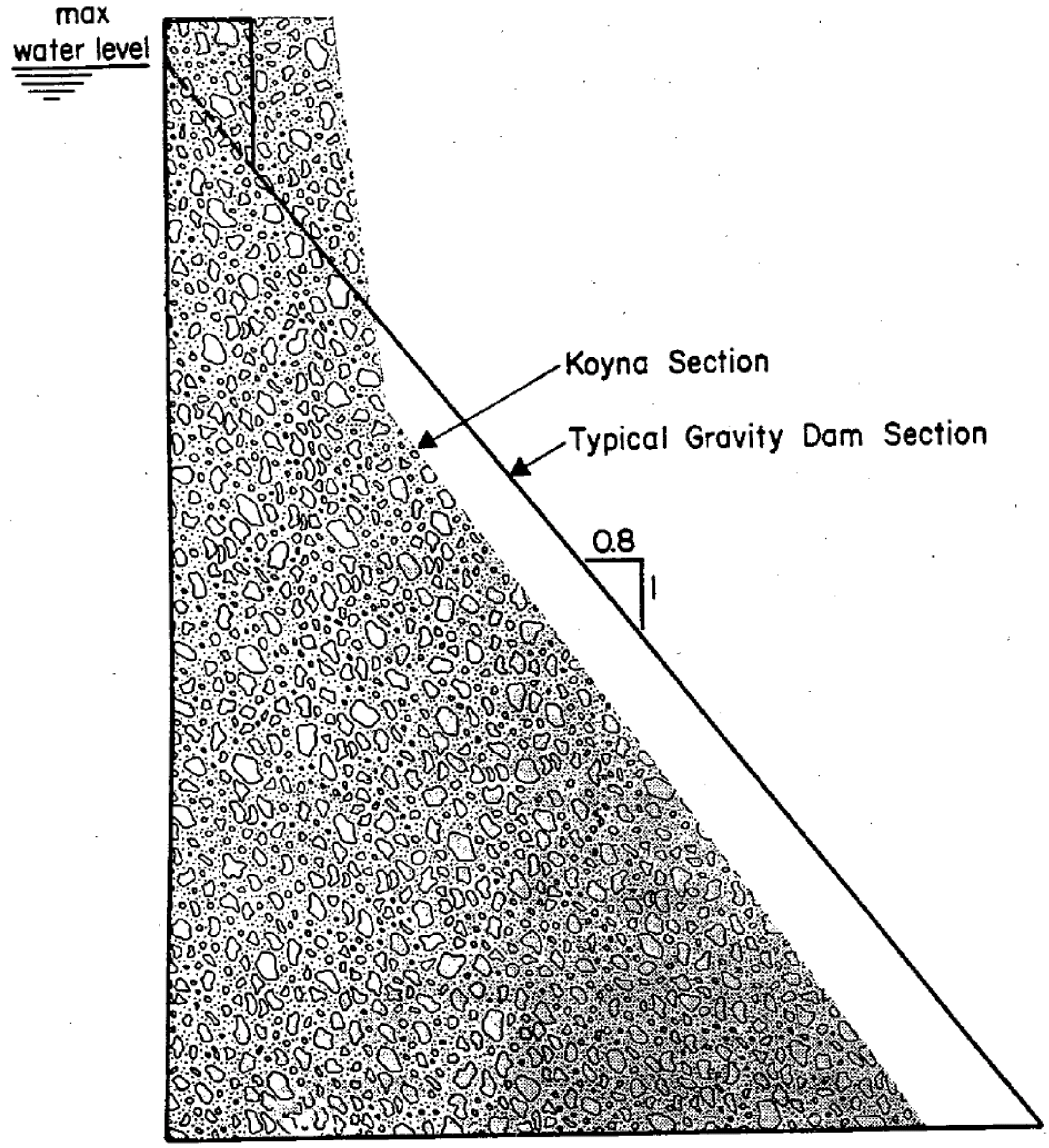

Figure 3: Koyna and Typical Gravity Dam Sections