POTENTIALLY ACTIVE FAULTS IN THE FOUNDATIONS OF LARGE DAMS PART II: DESIGN ASPECTS OF DAMS TO RESIST FAULT MOVEMENTS

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ABSTRACT

The guidelines for the design of dams on foundations with potentially active faults, as given in ICOLD Bulletin 112, are reviewed. For embankment dams, the general approach to mitigate potential damage to the dam caused by fault movements consists in selecting the proper materials and defensive design. The idea is to reduce the vulnerability of the dam zones to cracking and subsequent erosion. For concrete dams, it may be possible in certain cases to accommodate slip along a fault by structural measures in the form of a slip joint in the dam. Some case histories illustrate the measures taken or proposed for two embankment and three concrete dams.

KEYWORDS: Active faults, concrete dam, rockfill dam, earthquake safety, vulnerability of dams, slip joint

1. INTRODUCTION

Part I of this paper (Wieland et al., 2008) discusses the vulnerability of dams to seismic movements in dam foundations and as well problems in connection with possible movements along discontinuities in the dam foundation during a strong earthquake. Selected case histories are also described briefly. The suitability of different dam types on active faults is evaluated in view of their damage potential and very approximate limits for tolerable displacements are presented. The main objectives of this second part of the paper are (i) to present case histories illustrating structural and design measures which were implemented with both embankment and concrete dams founded on potentially active faults, and (ii) to provide guidelines for dams to be built at locations where displacements along discontinuities in the footprint of a dam may occur during a strong earthquake.

2. GUIDELINES FOR DAMS ON FAULTS

In 1998 the International Commission on Large Dams (ICOLD) published a guideline on Neotectonics and Dams (ICOLD, 1998), which addresses the issue of dams on active or potentially active faults. The expression potentially active is used to indicate that there is either no clear evidence on the activity of a fault or the activity has not taken place in recent time (e.g. Holocene period). But with increasing safety demand and the introduction of probabilistic safety analyses the seismic hazard has to be specified for return periods exceeding the typical 10,000 years used in dam engineering. Once the return period is increased then faults, which previously were considered as inactive from the point of view of dam safety may then be considered as potentially active or active. Such a development is not unproblematic as many dams are located at sites with rather complex foundation conditions.
Obviously, no dam engineer wants to build a dam on an active fault and no dam engineer would admit that he has done this intentionally, especially for dams which are vulnerable to fault movements such as concrete dams and in particular arch dams. In some countries such dam sites are taboo and another dam site is selected with superior seismotectonic conditions. However, in regions of high seismicity such as, for example, the Zagros mountain range in Iran, major faults crossing a dam site could become active anytime and such faults are encountered at almost all dam sites. Small and short faults are only a problem when they are located very close to a major fault, which can produce large magnitude earthquakes. Then, depending on the geological conditions, movements along

a major fault (e.g. of first order) may involve the near-fault zone as well. The basic statements relevant for dam engineers given in the Bulletin 112 (ICOLD, 1998) can be summarized as follows:

1. When a major active fault is crossing the dam foundation the site should be abandoned and a more appropriate site should be looked for.
2. In highly seismic areas it may not be possible to find any site without fault slip hazard: In such a case, concrete dams should be avoided and preference be given to a conservatively designed embankment dam, designed with ample filter and transition zones, on both sides of a rather wide core, displaying ductile properties. There is a considerable confidence that such a structure can withstand, without failure, significant fault offsets.
3. If the seismotectonic conditions at a dam site are not clear, then the engineer should avoid concrete dams and select a conservatively designed embankment dam.

Sherard et al (1974) arrive at similar conclusions. The authors state that (i) concrete dams on active faults, or near some major active faults, are not advisable, and (ii) if a site with fault movements cannot be avoided then it is reasonable practice to construct a conservatively designed embankment dam. These statements still hold true today.

3. DESIGN OF DEFENSIVE MEASURES FOR EMBANKMENTS WITH POTENTIALLY ACTIVE FAULT IN THEIR FOUNDATION

3.1 General guidelines for defensive measures

The basic ingredients of an embankment dam, which can resist both differential ground movements and strong earthquake ground shaking, are the following:

1. Impervious core made of ductile material with a high failure strain to minimize the propagation of the rupture zone; prevention of internal erosion if core is cracked;
2. Thick filter and transition zones: about 50% shall still be available after faulting and slip movements;
3. Wide dam crest;
4. Flat slopes;
5. Generous freeboard: to prevent overtopping due to impulsive waves in reservoir and settlement of the dam crest;
6. Material selection and compaction of rockfill, etc.

The main concern of any embankment dam with impervious core is the erosion resistance of the core material. According to Sherard (1967) ‘the filter and transition zones provide the first line of defense against earthquake-induced concentrated leaks through the dam. If thick, adequately graded, cohesionless transitions are provided, a leak can only get out of control in extreme cases of embankment distortion caused by foundation movement’.
‘Where there is a choice between several types of materials for the core of a dam, which may be subject to an earthquake, it seems apparent that the resistance to concentrated leakage should be the main factor in the decision.’
An approximate classification of core materials on the basis of resistance to concentrated leaks was also made by Sherard as shown below:

1. Very good materials: Very well-graded coarse mixtures of sand, gravel, and fines.
2. Good materials: (i) Well-graded mixtures of sand, gravel, and clayey fines; (ii) highly plastic tough clay (CH) with plasticity index greater than 20.
3. Fair materials: (i) Fairly well-graded gravelly, medium to coarse sand with cohesionless fines; (ii) clay of medium plasticity (CL) with plasticity index greater than 12, (iii) coarse mixtures of sand, gravel, and fines

Very poor materials are (i) fine, uniform, cohesionless silty sand; (ii) silt from medium plasticity to cohesionless (ML) (plasticity index less than 10) because these materials are highly erodible.

3.2 Case histories

3.2.1 Cedar Springs dam

Cedar Springs Dam is a 76 m high zoned earth-rockfill dam in California, USA, completed in 1972. The downstream two thirds of the foundation consist of granite-type rock, while the upstream third is composed of slightly indurated silty sand (Harold formation). There are several faults in the foundation, Faults 1, 2, and 5 being the most significant ones. Faults 1 and 2 separate the Harold formation from the granitic basement rock. Fault 2 splays from Fault 1 near the middle of the stream channel (Fig. 1). The width of Fault 1 is around 25 m and for Fault 2 it varies from about 0.6 to 3.5 m, but at the splay the width of Fault 2 grows to nearly 20 m. Both faults dip nearly vertical. Movements in the recent alluvium indicate a displacement of about 1.5 m in vertical direction.

The dam site is within the San Andreas/San Jacinto fault system which is considered capable of producing earthquakes of magnitude 8+. The distances to three major active faults, namely the San Andreas, San Jacinto and Cleghorn Faults are about 10, 14 and 3 km respectively and the PGA at the dam site has been estimated as 0.55 g.

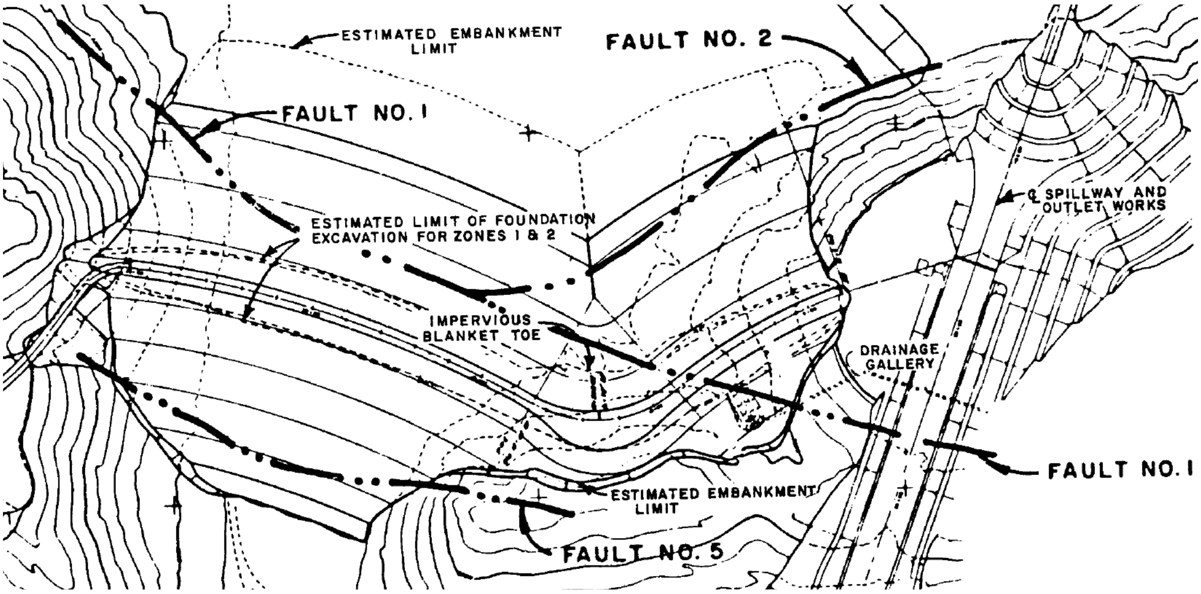

Figure 1: Cedar Springs dam: Layout of embankment showing three active faults in the dam foundation (Faults 1, 2 and 5) after Kollgard and Chadwick (1988)

The seismic design assumed a 1.0 to 1.5 m displacement in the foundation with the reservoir under high flood conditions and the spillway working under its maximum capacity. Among the many design provisions adopted for mitigating possible earthquake damage to the dam, the following are of particular interest:

(1) Concave downstream curvature of the two wings of the dam, so that downstream movements will tend to compress the core; (2) Thickening of the core in the area of the convex downstream bend and on the left abutment where Fault no.1 passes under the core; (3) Alignment of the dam axis such that founding of the core on known faults can be minimized; (4) Removal of all alluvial material below the dam to eliminate the possibility of liquefaction; (5) Freeboard 10 m above maximum operating water level and 1.5 m above maximum probable water surface. The dam so far has not been subjected to a strong earthquake.

3.2.2 Rogun dam (Tajikistan)

Rogun dam on the Vakhsh river in Tajikistan was originally designed in the 1960s and 70s and construction works began in 1976. They were suspended in the early 90s with the collapse of the Soviet Union. The original project (Fig. 2) comprised a 335m high earth-rockfill dam with central impervious core. The project is located in a region of high seismicity caused by the convergence of two tectonic plates. First and second order faults are only some 10 to 20 km from the dam site. The bedrock at the dam site consists of sedimentary rock of Mesozoic age, mainly sandstones and mudrock with a few calcareous beds. Two regional third order active reverse faults of about 100 km length frame the dam site. They move with a rate of about 1 mm per year and the cumulative displacement has reached about 1 km. Both faults are connected to a salt stratum at depth which provides a lubricating effect. The displacements on one of these faults, the Yonakhsh Fault, occurs mainly as aseismic creep. They induce brittle events of small magnitude in the adjacent strong sediments. Hence, small magnitude earthquakes are very frequent at the dam site and its vicinity. The Yonakhsh Fault crosses the future reservoir and will become submerged. The salt wedge, which is squeezed to the surface along this fault, is vulnerable to leaching and would therefore need protection. There are also higher order faults (sympathetic faults) crossing the foundation which may slip when on the first and second order faults large shocks would occur. The original design (Fig. 2) illustrates these faults in the dam foundation. However, it was feasible to place the core on a wedge bounded by two faults such that the footprint of the core remained free of fault traces. Faults, however, do pass through the foundations of the shells of the dam.

Recently, a new feasibility study has been carried out which foresees to construct the dam in three stages (Schmidt, 2007). The study also investigated the feasibility of other dam types but considering the many uncertainties with the quality of the bedrock and the prevailing seismicity, the embankment dam was found to be the most reliable alternative.

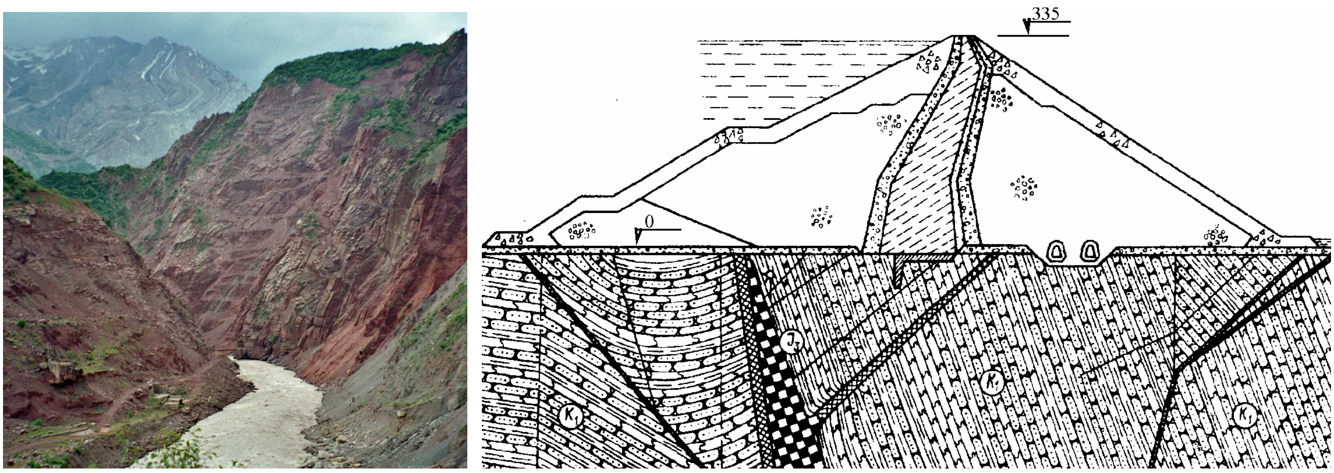

Figure 2: Left: View of Rogun dam site at the river bend looking towards downstream, Right: Original cross section of 335 m high dam as designed by Hydroproject Tashkent (right)

4. STRUCTURAL MEASURES FOR CONCRETE DAMS ON FOUNDATIONS WITH POTENTIALLY ACTIVE FAULTS

4.1. The concept of a slip joint

Concrete gravity dams may be feasible if the fault plane is almost perpendicular to the dam axis, the direction of the movement is known reliably, and the fault thickness is in the range of decimeters. In this case it would be possible to design a slip joint, which should be able to cope with the probable deformations. The following three case histories illustrate this feature.

4.2 Case histories

4.2.1 Morris dam

Morris dam completed in 1934, is a concrete gravity dam with a height of 100 m (Kollgard and Chadwick, 1988). The dam is located in an area of very high seismicity. The nearest distance to the San Andreas fault is ca. 27 km and the Sierra madre fault is within 2.7 km of the dam site. The foundation of the dam has a number of faults (Fig. 3) and the engineers and geologists assumed that there could be movement on one particular fault. Therefore, the transverse joint between blocks 8 and 9 shown in Fig. 4 was aligned with the fault and provided with sliding planes, gaps and mastic filling to allow at least 90 cm of movement along this joint without affecting the stability of the dam. During the maximum fault movement the space between blocks 8 and 9 will either close to zero or open to 1.8 m from the present gap of 0.9 m. The maximum movement this joint can accommodate is about 1.8 m. Up to now no tectonic movements have been reported.

4.2.2 Clyde gravity dam

The 102 m high Clyde gravity dam in New Zealand (Hatton et al., 1991) is built across a potentially active fault intersecting the dam site. For that purpose a slip joint through the dam was provided to allow for fault displacements. The dam is located in a relatively wide valley. In early assessments the main river channel fault and other faults crossing the dam site were considered as inactive. At that time an active fault was one that had repeated movement within the last 500,000 years or a single movement within the last 50,000 years (Hatton et al., 1991).

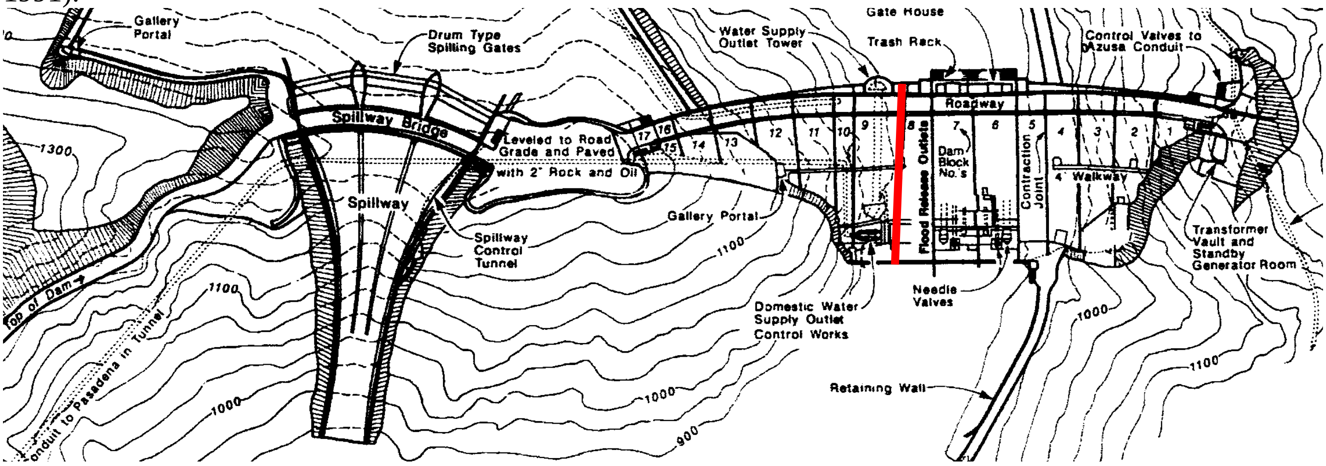

Figure 3: Plan of Morris gravity dam with slip joint above fault between blocks 8 and 9 shown in red

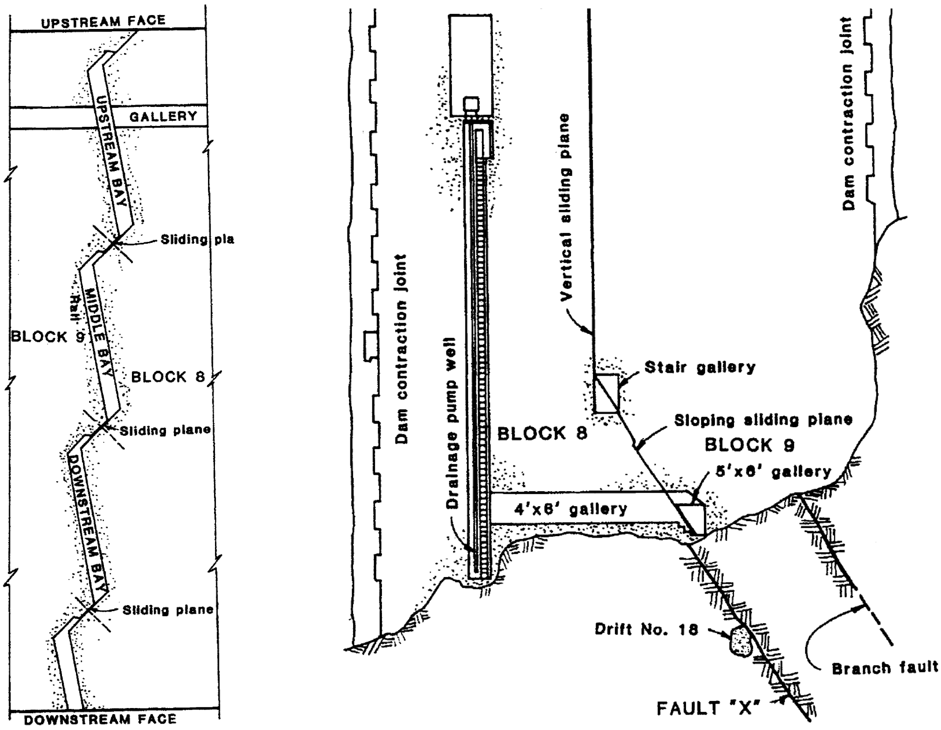

Figure 4: Morris gravity dam: Plan of slip joint between blocks 8 and 9 (left) and profile of joint along dam axis (right) after Kollgard and Chadwick (1988)

A seismotectonic hazard assessment of the dam site indicated that a major rupture of the nearby Dunstan fault (magnitude 7 to 7.5) could induce up to 20 cm sympathetic movement on the river channel fault. Therefore, the dam design was modified by providing a slip joint in the dam above the fault. The slip joint can accommodate a 2 m displacement of the fault in strike slip sense and 1 m in a dip slip sense, either normal or reverse movement. Details of the slip joint are shown in Figs. 5 and 6.

An essential feature of the slip joint was to provide contact between adjacent dam blocks that are parallel to the dip and strike of the fault so that the joint can accommodate any in-plane fault movement. Where the joint is vertical in the dam it needs to be kept open for reverse movements. The open joint was kept watertight by a wedge plug that extends up the full height of the dam. Special detailing of the base of the wedge was needed to limit any seepage in this zone due to the movement of the wedge, Up to now no movements have been observed along the river channel fault.

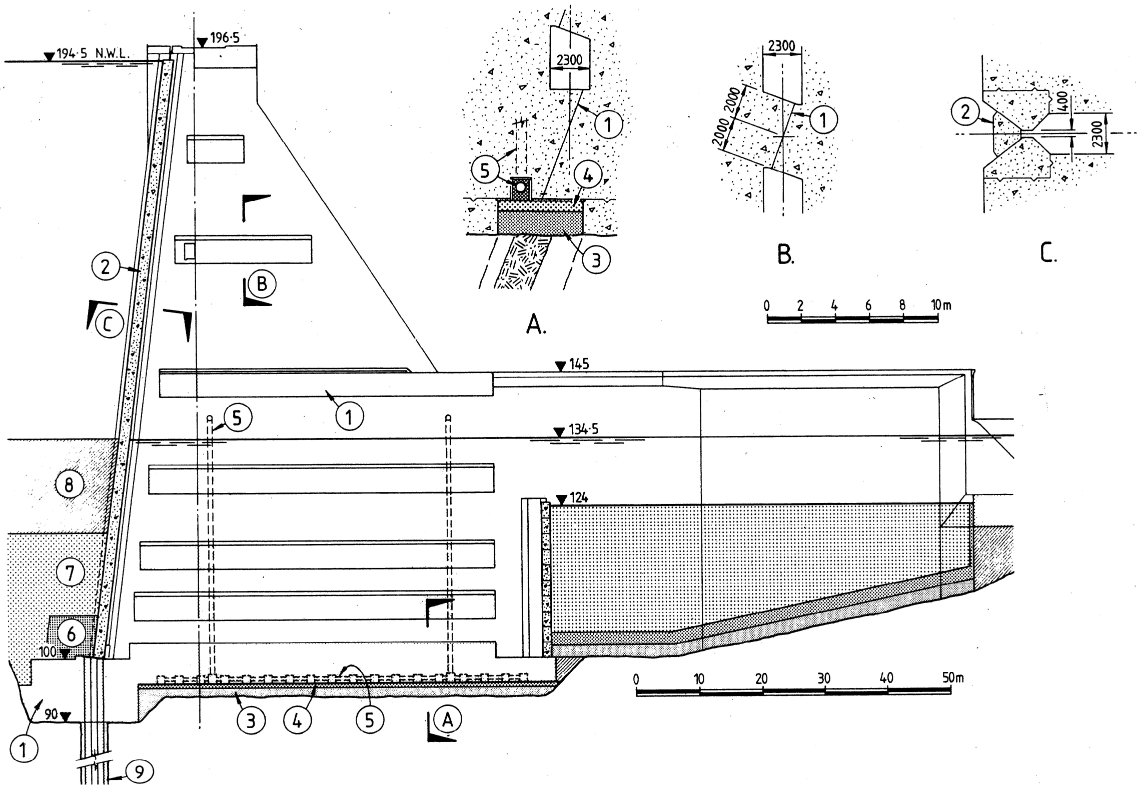

Figure 5: River channel fault joint of Clyde gravity dam in New Zealand (Hatton et al., 1991) (Explanations: 1. Contact surfaces; 2. Wedge plug; 3. Filter zone; 4. Drainage zone; 5. Drainage pipe; 6. Riprap; 7. Gravel blanket; 8. Low permeability blanket; 9. Cutoff shaft)

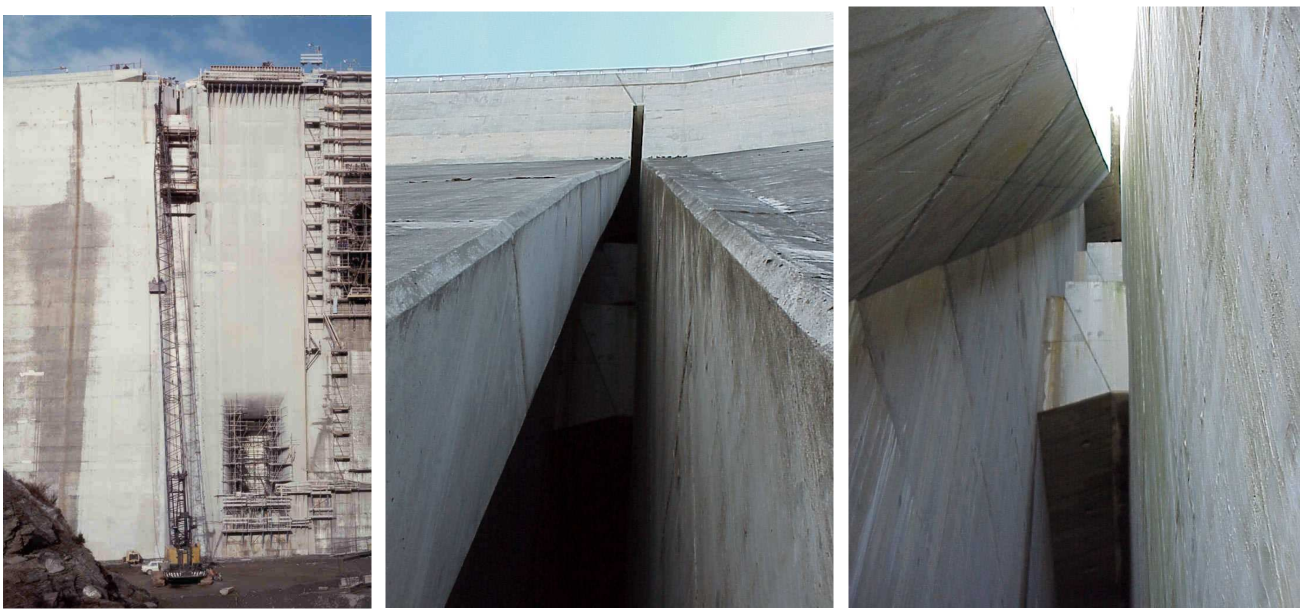

Figure 6: Details of slip joint at Clyde dam: construction of wedge plug at upstream face (left); downstream view of open slip joint (centre); detail of sliding contact surface at open joint taken from downstream (right) (Photos Courtesy P.F. Foster)

4.2.3 Steno arch dam

For the proposed 185 m high Steno double-curvature arch dam in Greece, which is located at a site with a potentially active fault in the foundation, a special design was developed, which included a peripheral joint and a horizontal slip joint as shown in Fig. 7 (Gilg et al., 1987). The design criteria required that the arch dam should withstand, without serious damage, small fault movements up to a few centimeters and not collapse under larger movements of some decimeters. To check the viability of the proposed joint system, special model tests were carried out. It was concluded, based on these tests, that the dam can withstand horizontal movements in the order of 5 cm to 10 cm without damage. Larger movements up to 100 cm caused significant distress in the dam. The dam has not been built. Additional investigations will be needed before such a dam can ever be built.

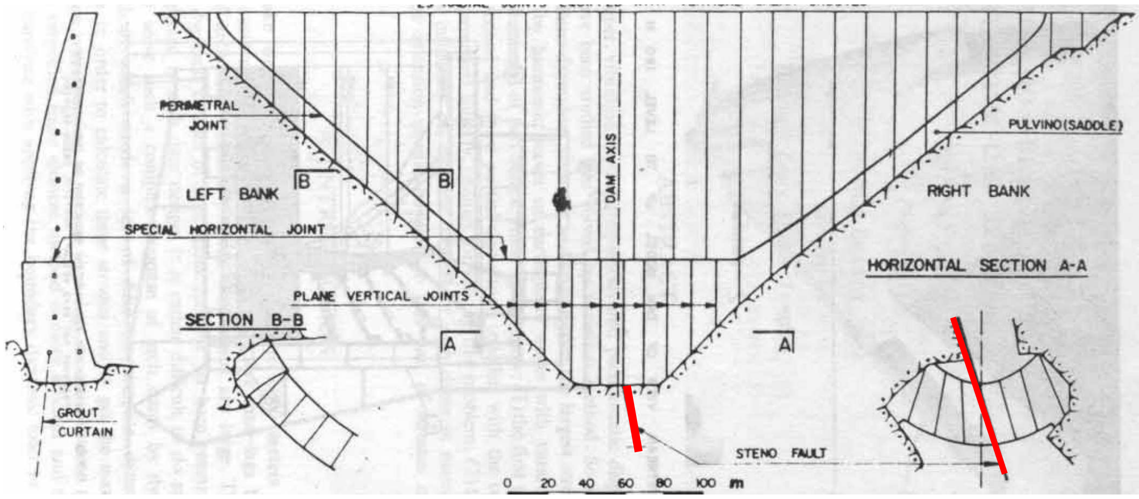

Figure 7: Proposed Steno arch dam with joint system to cope with potentially active fault at the base of the dam (Gilg et al., 1987)

4.3.4 Other concrete dams on potentially active faults

In Iran most dam sites are located in highly seismic regions. Besides high intensity ground shaking there is also the hazard of fault movement at some of the sites. Mahdavian and Nayeb (2005) have discussed two dams on faults.

The first dam is the 83 m high Shirvan (or Barezu) double-curvature arch dam, which is constructed on an active fault with an estimated fault movement of 20 cm. The fault is located in the upper part of the left abutment. In the original design this fault was not taken into account. Later different alternatives and modifications in the dam design were proposed by e.g. providing a concrete pad in the abutment rock and vertical joints in the dam body which allow fault displacements, where the fault intersects with the footprint of the dam. It is not clear which modifications were actually implemented. The dam has been completed.

The second dam is the 158 m high Rudbar Lorestan gravity dam where a fault with almost vertical fault plane intersects the footprint of the proposed concrete dam at the left abutment. A slip joint similarly to that used in Clyde dam was proposed. The tectonic situation has some similarity with Clyde as there is also a major fault at a distance of 1.6 km from the dam site. However, the seismotectonic situation is very complex, especially in terms of possible displacements along discontinuities in the footprint of the dam. Also the valley is very narrow resulting in a crest length to dam height aspect ratio of about 1 (Fig.8). The optimum dam type is under study.

5. CONCLUSIONS

Today, dam engineers are often confronted with difficult dam sites. Some of these may be located in regions of high seismicity and there may even be potentially active faults passing through the footprint of the proposed dam. The case histories presented in this paper demonstrate that both embankment (fill) dams and concrete dams have actually been constructed over faults by implementing special measures, i.e. defensive design with embankment dams and structural measures in the form of a slip joint with concrete dams. The suitability of theses measures, however, has never been put to test since these dams have never been subjected to fault displacement. Caution is therefore required. Concrete dams can be quite resilient to strong ground shaking but they are very sensitive to small displacements in their foundation. Embankment dams have less problems with movements along discontinuities in the footprint of the dam if properly zoned.

In highly seismic areas it may not be possible to find any site without fault slip hazard. In such a case, concrete dams should be avoided and preference be given to a conservatively designed embankment dam, designed with ample filter and transition zones, on both sides of a rather wide core, displaying ductile properties. There is a considerable confidence that such a structure can withstand, without failure, significant offsets at discontinuities in the footprint of a dam.


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Figure 8: Rudbar Lorestan dam project in Iran: View from upstream to narrow gorge of dam site (left) and fault surface perpendicular to dam axis at left abutment (right)

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