POTENTIALLY ACTIVE FAULTS IN THE FOUNDATIONS OF LARGE DAMS PART I: VULNERABILITY OF DAMS TO SEISMIC MOVEMENTS IN DAM FOUNDATION

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ABSTRACT

The implications of (i) movements caused by active or potentially active faults passing through the foundation of a large dam, and (ii) movements of blocks in the dam foundation caused by strong earthquakes at a fault close to a dam site, on the design of dams and their safety are discussed. The vulnerability of concrete dams to differential foundation movements is illustrated with the damage observed at the Zeuzier arch dam in Switzerland. Faults in dam foundations are an important issue in dam safety assessments and defensive measures to be taken when a dam is located in an area where it is not clear whether movements are possible along faults during strong ground shaking are recommended. Very approximate numerical values of tolerable displacements are also presented.

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

1. INTRODUCTION

During strong earthquakes the most severe condition for a dam is when it is subjected to both ground shaking and movement of faults and other discontinuities in its footprint. However, for dam engineers primary attention is usually given to ground shaking while the possibility of surface fault breaking or block movements in the dam foundation is often disregarded. Surface fault breaking, or more precisely, surface slip along an identified fault zone under the dam, was always understood to be the most damaging tectonic process that can affect a dam. The tendency and also the need to make use of less favourable dam sites, and the awareness that the hazard of foundation movements is about the most severe incident that could affect the structural integrity of dams, should be considered and analysed when indicated by prevailing tectonic conditions.
Tectonic movements result generally in the formation of fault breaks and in creep movements. In connection with fault breaks also block movements have to be considered as a possible mechanism, especially in the near-field of major faults, which are capable of producing large earthquakes. Such blocks can be formed by joints, bedding planes, shear zones, and higher order faults. Both, fault breaking and creep movements constitute the crustal mobility, which can directly affect dam sites. In the subsequent part of this paper the effect of creep movements is not discussed as this effect is of quasi-static nature and less severe than the sudden slip along a fault or the movement of blocks during a strong earthquake.
Faults with surface breaking capability crossing the dam site and potential block movements are the main points of interest for the safety of dams subjected to strong earthquakes. Consequently, recognizing such features is the decisive step in the problem. If the existence of such features has been determined in a dam foundation, the best policy is to look for a tectonically more stable alternative site. If this is not possible, then a conservatively designed embankment dam might be an acceptable solution if the expected differential movements can be absorbed by its sealing and drainage zones, without provoking a dam failure.
Therefore the definition of an active (or potentially active) fault is very important and quite sensitive. However, Allen and Cluff (2000) stated that there is no sharp division into “active” and “inactive” faults. Modern geologic studies in combination with improved age-dating capabilities have shown that there are in fact all

degrees of fault activity and any categorization is arbitrary.
It is quite obvious that a time mark is needed for identifying fault movements. This is usually a soil or rock surface, for example in a trench, offset by a fault. Dating of fault gauge has not been reliable so far. The consequences of dam failure may also play an important role on how conservative one should be when selecting potentially active faults. It is also important to note that in view of new information and assessment techniques, faults, which in the past were considered as inactive, might now be considered as active or potentially active.
In the past, faults with no clear evidence of (instrumentally recorded) activity were considered as inactive, however, today faults where there exist no proofs that they are inactive, are assumed as active or potentially active. The first approach might have been too optimistic and the latter might be too pessimistic especially in regions of high seismicity, where most faults have to be assumed as potentially active. Minor faults are not of concern as they are not capable of causing important earthquakes or surface fracture with significant movements. However, such faults and discontinuities may be of concern, if a major fault where large magnitude earthquakes can occur is located close by.
Tracing and dating the active tectonic phenomena into geologically recent past is a difficult problem. In each case, the question whether the considered fault is active or not needs a clear answer: yes or no. The answer to this question has most serious consequences for the design and type of the dam which is being considered.
This paper consists of two parts, i.e. in Part 1 the vulnerability of dams to seismic movements in dam foundations discussed and Part 2 is concerned with design aspects of dams to resist fault movements (Wieland et al., 2008).

2. EFFECTS OF ACTIVE TECTONIC FEATURES ON SELECTION OF SITES AND DAM TYPE

The existence of historical or instrumental data on surface fault breaking is very important. But the time span for which such data are available is generally far too short. Large surface breaking events might be separated by thousands of years. Hence, the related investigations have to cover the full scope of geological, seismological, geophysical and geodetic information, including remote sensing, trenching, adits, exploratory borings and geochronological dating, etc.
Fault slips or block movements under the dam during strong earthquakes, are considered to be the most loading conditions for the structural integrity of dams. Creep movements, rather slow and uniform, can be monitored and may be amenable to mitigating measures.
If a fault crossing the dam site is evaluated as potentially active, the next question is what size of fault movements is to be expected, as the size expresses its damage potential. Correlation of the length of faults with earthquake magnitude and displacement along the fault, supplies such information. A comprehensive elaboration is given by Wells and Coppersmith (1994), based on analyzing world-wide data. Several correlations are presented so that the size of fault break displacement can be estimated.
The tectonic activity assessment plays a key role in selecting sites and types of dams. Adequate studies and investigations have to be performed. When comparing dam sites, a reduced level of tectonic uncertainties should be rated as a significant advantage. Hence, evaluating the safety of any large dam with respect to fault slip and block movement hazards should be introduced as constant practice.
Still, there are cases where no geo-dynamically favourable alternative is available so that a decision might be taken to build a dam facing 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 considerable confidence that such a structure can withstand, without failure, significant fault offsets. Such a dam should be even more effective against fault creep and other foundation displacements.

3. POTENTIALLY ACTIVE FAULTS IN DAM FOUNDATIONS – CASE STUDIES

A comprehensive discussion of potentially active faults in dam foundations was given by Sherard et al. (1974). It contains information on existing dams founded on active faults, a summary of lessons learnt from historic dam breaks and fault mechanisms, and opinions by the authors regarding the design of dams on active faults.

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.

The above statements still hold true today as well as their introductory statements of the paper: *'In earthquake regions faults are frequently found to exist in dam foundations. Evaluation of the likelihood that displacement could occur along the fault during the lifetime of the dam, and the selection of the design details to ensure safety against such possible fault displacement, are difficult problems for which there is* (still) *little guidance in the literature.'*

Several case studies are given in the ICOLD Bulletin 112 (1998) whose main author is A. Bozovic. This bulletin represents the international state-of-the-practice for dams on potentially active faults. Selected case histories described in the recent literature are summarized below.

1. The Upper Crystal Springs Dam first served as a dam and was then submerged by a downstream structure. The 1906 San Andreas fault break has sheared the dam and offset it by 2.5 m. (Note: The 43 m high Lower Crystal Springs curved gravity dam successfully resisted the extreme ground shaking of the 1906 San Francisco earthquake.)

2. The 143 meters high Tarbela Dam (completed in 1974), built on river Indus in Pakistan is a good example of significance of active faults studies. The dam was designed without consideration to a fault (Darband fault) crossing the dam foundation, which was revealed during the construction stage. A detailed seismotectonic study at later stage proved the fault to be active. The seismic design parameters had to be revised by taking into consideration the active fault passing below the dam body. The effect of surface rupture on Darband fault beneath the embankment was also reviewed. It was estimated that movements of 1 m to 1.5 m could occur on this fault. It was believed that if such a movement did occur on the Darband fault no catastrophic failure of the embankment would result, since the core of the embankment is constructed of self-healing material with a transition zone and a wide chimney drain on the downstream.

3. The Matahina Dam in New Zealand is a rockfill embankment 82 m high and 400 m long, with a central core. This dam has leaked after first filling in 1967 due to core cracking, and was subsequently repaired. In 1987 the dam was exposed to strong seismic shaking (peak horizontal crest acceleration 0.42 g) due to a magnitude M_L6.3 earthquake, located on the Edgecumbe Fault. Significant rehabilitation work was performed in 1988 due to internal erosion of the core at the left abutment. The dam is sited across a part of the Waiohau Fault Zone, 80 km long. The fault is active with proven surface fault breaking during the Holocene. Several prominent strands of the Waiohau fault intersect the dam site and are considered capable of rupturing during the lifetime of the Matahina Dam. Investigations in trenches showed that movement on the fault had occurred four times during the past 11,300 years. It was assumed that movement could occur on any of the fault traces present within the dam site. The design criteria, estimated at the 84th percentile level, assumed the magnitude of the Safety Evaluation Earthquake (SEE) as M_w7.2 with corresponding horizontal and vertical peak ground accelerations of 1.25 g and 1.35 g respectively and 3 m of oblique slip on the fault (i.e. 2.7 m horizontal and 1.3 m vertical). Such displacements would surely result in major cracking of the dam body inducing piping and internal erosion (as evidenced by observed core erosion during the 1987 Edgecumbe earthquake). Therefore, it was decided to strengthen the dam with a leakage resistant buttress (Gillon et al. 1997; McMorran and Berryman, 2001).

4. Aviemore Dam in New Zealand is a composite structure consisting of a 364 m long and 56 m high concrete gravity dam and a 430 m long and 49 m high zoned earth embankment with upstream sloping core. There is a 1 m thick filter separating the core from the downstream pervious shoulder and serving as a drainage blanket on the bottom of the core trench under the shoulder. The Waitangi Fault was recognized in the foundation excavation. From trenches it could be observed that this fault had a late Quaternary displacement of 1 – 2 m and that the most recent displacement took place about 14,000 years ago. The fault crosses the footprint of the embankment dam and strikes normal to the dam axis. Waitangi Fault was assessed as being capable of a magnitude 7.0 event and with a peak ground

acceleration of 1.0 g. For the fault a vertical separation of 1.2 m and a horizontal to vertical ratio of 1H:3V were adopted for the SEE fault surface displacement. To analyze the performance of the embankment under the SEE fault break, a three-dimensional numerical model was created. It showed that the zone of embankment deformation would be several tens of meters long. Cracking of the core is expected to occur over a 40 m long zone, mainly in transverse direction. Cracking would take place from the crest downwards to a depth between 5 and 10 m. The filter is expected to remain continuous across the zone of faulting. The fault in the foundation is of low permeability and it would be expected that no concentrated leaks would develop as a result of fault displacement. However, in the post-earthquake phase, the fault rupture may provide a mechanism for continued erosion (Mejia et al., 2005).

5. Shih-Kang weir, located at the Da-Jia river in Taiwan, comprises two sluiceways and 18 spillway gates. The concrete gravity dam has a height of 25 m and a crest length of 357 m. On September 21, 1999 the weir was severely damaged during the magnitude 7.3 Chi-Chi earthquake and the reservoir with a volume of 2.7 million m^3 was released through spillway gates 17 and 18. The spillway was designed for a total discharge of 8,000 m^3/s. The uncontrolled release of the reservoir through two openings did not cause any flooding in the downstream area of the dam as the total discharge was much less than the design discharge of the whole spillway (Wieland et al., 2003). The weir was damaged (i) by the rupture of segments of the Chelungpu fault, (ii) by surface movements, and (iii) by strong ground shaking. The most spectacular damage occurred at spillways bays 16 to 18 near the right abutment and was due to fault movements (reverse faulting) of several metres mainly in vertical direction. However, there was widespread cracking on the whole structure. In addition, the irregular ground movements caused separation of most of the blocks from the foundation rock, which consists of layers of mudstone, siltstone and sandstone. Thus, five of the spillway gates and one sluice gate were inoperable after the earthquake. Moreover, all the simply supported spans of the bridge across the weir fell off the bearings. The dam, which was completed in 1977, was designed against earthquakes using a seismic coefficient of 0.15. There exists no direct information about the peak ground acceleration (PGA) at the dam site. However, the strong motion station closest to the dam recorded PGA-values of 0.51 g and 0.53 g in horizontal and vertical directions, respectively. During excavation of the foundation no clear evidence of a fault in the dam foundation was found. The earthquake induced ground movements at Shih-Kang weir are rather complex as the Chelungpu fault splits up into different sub-faults in this area, one of them crossing the weir and destroying the spillway gates at the right abutment. Another fault branch crossed the intake tunnel at the left abutment and sheared it off. The Shih-Kang dam is an important case study as it is the first large concrete dam, which has been exposed to substantial fault movements. The lessons learnt are expected to have an impact on similar projects.

4. VULNERABILITY OF CONCRETE DAMS TO NON-UNIFORM GROUND MOVEMENT

Concrete dams are very vulnerable to non-uniform foundation movement as shown in the case of the 154 m high double curvature Zeuzier arch dam in Switzerland (Fig.1). Cracks formed in the dam body in 1978/1979 due to deformations of the abutments caused by movements in the dam abutments generated by the drainage of the rock. The latter resulted from the construction of a pilot tunnel for a highway, near the reservoir. Relative foundation movements of a few cm have caused severe cracking in the dam (Amberg and Lombardi, 1982).
Moreover, the prediction of dynamic response of the cracked dam during strong ground shaking combined with fault movement in the dam foundation is an extremely difficult task as the crack pattern due to foundation movement is very hard to predict. Therefore, different types of cracking scenarios must be considered. It must also be assumed that strong ground shaking is acting on the dam, when the main cracks due to non-uniform ground movement have already been developed, i.e. the dynamic behaviour of the cracked dam has to be assessed.
As shown in Fig. 2 for the Zeuzier arch dam, it is quite straightforward to extend the main crack such that the detached top portion of the dam will fall into the reservoir under earthquake ground shaking. In order to show how a rigid concrete dam behaves under the combined action of non-uniform foundation movement and strong ground shaking, shaking table tests may have to be performed as present analyses methods used by dam engineers may not allow the prediction of crack patterns in a three-dimensional concrete dam.

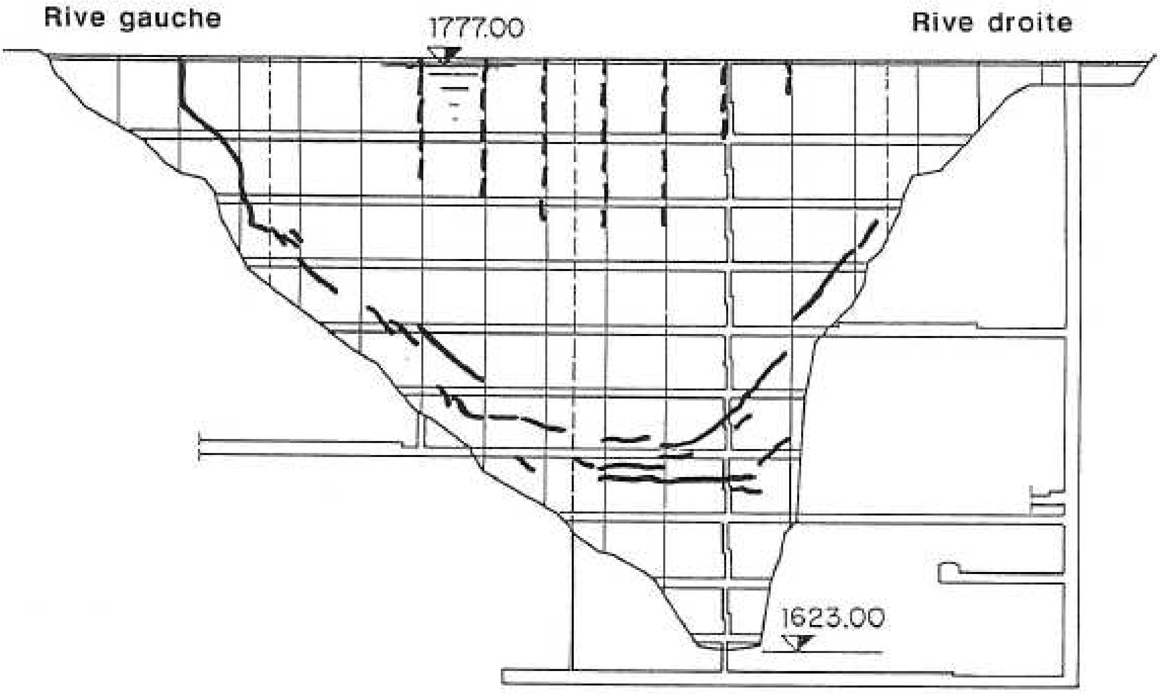

Fig. 1: Crack pattern in Zeuzier arch dam caused by non-uniform foundation movements of a few centimetres (solid line: cracks at downstream face; dotted line: cracks at upstream face) (Amberg and Lombardi, 1982)

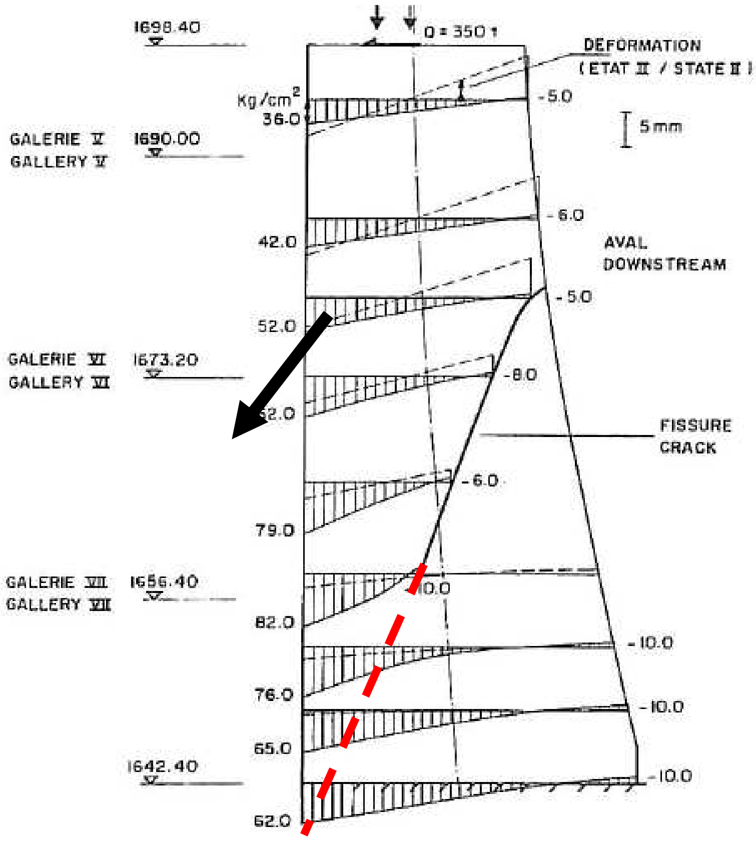

Fig. 2: Observed cracking in upper portion of Zeuzier arch dam and possible extension of crack under earthquake ground motion (dotted line) causing failure of the upper portion of the dam into the reservoir (assumed failure scenario) (Amberg and Lombardi, 1982).

Zeuzier dam has been repaired and is back in operation. But the impact of this severe damage is felt today in Switzerland.
However, as mentioned earlier, there is very little experience with such types of foundation movements. It is certainly very dangerous for most concrete dams. Therefore, in connection with the ongoing construction of the 57 km long Gotthard railway tunnel in Switzerland a very sophisticated dam monitoring system was installed in the concrete dams located above the tunnel to monitor, at the dam sites, the deformations caused by the excavation of the tunnel some 1000 m below the dams and, similarly, to record possible changes in the groundwater regime in the vicinity of the dams. The acceptable movements are only in the order of a few cm for arch dams. This shows that the issue of foundation movements in concrete dams is taken as a very serious dam safety issue.

5. SELECTION OF DAM TYPES

In designing dams for fault movements the following situations have to be considered:

- (i) active fault of small width passing through the dam foundation: a concrete gravity dam is theoretically possible if the valley is wide;
- (ii) multiple faults passing through the dam foundation or fault with wide fractured zone: concrete dams are not possible; and:
- (iii) dam located in the near-filed of a major fault, which is capable of producing large magnitude earthquakes: if fault displacements spread as far as the dam site, they can cause movements along fractures or higher order faults in the dam foundation; a concrete dam is then not feasible; and
- (iv) dam located at large distance (tens of kilometers) from a major fault, which is capable of producing large magnitude earthquakes: all dam options are feasible

Concrete dams can only be considered when the location of any fault(s) in the foundation and the direction of future movements are known reliably. The design of dams on potentially active faults is discussed in part II of this paper.
In the subsequent part the implications of (mainly horizontal) foundation movements on different dam types and allowable displacements are given:

1. **Earth core rockfill dams (ECRD):** After a displacement, caused by the fault slip, the remaining overlapping filter zone should at least be 2 m. This means that with a design displacement of 1 to 2 m, a filter of at least 3 m thickness would be required. A safety factor of 1.5 may be added to cover all the uncertainties and one would end up with a filter thickness of about 4.0 to 4.5 m. The filter will have no cracks, because its material has to be perfectly cohesionless. This means that any opening that will be created during the displacement process will collapse when saturated. The clay material of the core should be more ductile over the fault zone, so that when it is sheared during the displacement it will not form open cracks which could provoke internal erosion. A horizontal (or strike-slip) displacement of 1 to 2 m in an embankment dam foundation can therefore be tolerated without problems.
   Bray et al. (1994) reported from experimental evidence that ductile materials with large failure strains can accommodate significant fault movements without actually breaking. The rupture would then not propagate to the top of the core and the zone of shearing would remain narrow.

2. **Concrete face rockfill dam (CFRD):** Displacement in the rock foundation will shear the plinth and rupture the perimetric joint sealing. Leakage will start through cracks in the plinth, the foundation (if the grout curtain is not wide enough) and through joints or cracks in the face slabs. This does not imply that the dam will collapse because the dam body, if properly zoned, can sustain seepage without washing out of the finer particles. The rockfill zones on the downstream side provide sufficient stability against the additional forces of seepage flow. These zones are free-draining and excess pore water pressures cannot develop. Still, the stability of the upstream slope under the changed hydraulic conditions (partial submergence and saturation of the transition zones in the dam body under the cracked face slab) has to be checked and verified.
   The plinth will require repairing which means that the reservoir has to be emptied (a bottom outlet is required) and the fill over the plinth has to be removed. If the horizontal displacement is less than about one half of the width of the plinth there is still a sufficiently wide continuous plinth slab, although

cracked, which can be repaired. The tolerable horizontal displacement in the foundation below the plinth of a CFRD should not be larger than about one fourth of the width of the plinth slab. Usually, the minimum width of the plinth (or toe) slab is 3 m, so that a displacement of 0.7 to 0.8 m could be accommodated. In vertical direction the displacement should not exceed one fourth of the thickness of the plinth slab.

The grout curtain will also have to be repaired. Seepage through the foundation can be minimized if at the location of the fault zone the grout curtain is made wider, i.e. consisting of several rows. The continuity of the grout curtain is then ensured even after the displacement.

The situation is different with certain older dams which may not have sufficient drainage capacity below the impervious face, for example, older asphalt-faced embankments. If the impervious face suffers cracking and the water penetrates through the cracks into the dam fill with inadequate means for fast drainage, the upstream slope will become hydraulically unstable. Such cases should be investigated by an analysis modeling transient water ingress through the cracks in the facing. For such embankments the tolerable displacements in the foundation may be on the order of 5 to 20 cm only.

3. **Concrete gravity dam (RCC or conventional concrete):** For rigid materials such as concrete, small displacements in the foundation will cause cracking. The extent of the cracking is very difficult to predict and also depends on the topography of the foundation. Cracks can, in general, be repaired, if their extent is within limits. However, in the case of an earthquake the dynamic behaviour of the cracked dam has to be predicted, which is beyond the currently available commercial analysis tools (no generally accepted or verified software is known to the authors). Again cracking in a gravity dam does not mean that the dam will collapse, since each block acts independently. The limit for fault displacements in the foundation may be set at not more than 0.10 m.

4. **Concrete arch and arch-gravity dams:** The same applies as for the gravity dam. Here a three-dimensional analysis of the cracking and the dynamic behaviour of the cracked dam is required. The limit for displacements depends on the valley shape and the geometry of the dam. In the case of an arch dam, the limiting displacements can be less than 5 cm. Much depends on the nature of the displacement. This is true for all concrete dams. Fault movements will cause cracks in almost all concrete dams, whereas differential foundation movements resulting, e.g. from the lowering of the ground water table are less critical and larger displacements can be accepted. Zeuzier dam in Switzerland, discussed above is a typical example.

Based on this discussion it can be concluded that the dam, which could best resist foundation movements is a zoned embankment dam.

The estimates of acceptable movements along discontinuities in the dam foundations given above are very approximate. They cannot be generalized as all dams are prototypes located at sites with specific local conditions.

6. CONCLUSIONS

The active tectonics being displayed at present constitutes a specific hazard, which has to be taken into consideration during design and safety evaluation of dams. The most dramatic scenario is the surface fault break through a dam foundation. Fault creep can also endanger the structural integrity of dams although in a less violent manner.

In spite of the fact that such active phenomena are rather infrequent, the existing risk is not negligible. When an active or potentially active fault in the dam foundations is recognized, far reaching consequences for the dam design must follow. This crucial evaluation must be formulated by the dam geologist and endorsed by the responsible dam design engineer who bears the individual responsibility for his dam.

The accumulated experience and evidence on fault movements indicate that it is necessary to define the engineering strategy. The possibility of surface fault breaks should, as a rule, be considered while designing dams or evaluating their safety.

In cases where recent tectonic activity of a fault crossing the dam site is recognized and it is not possible to find an alternative site, a conservatively designed embankment dam (with large filter and transition zones of noncohesive materials) is the type which offers best chances to survive the fault break effects. In general concrete dams should not be accepted for sites affected by active tectonic features.

The experience in evaluating the geodynamic hazard is accumulating and monitoring of seismic phenomena is steadily developing. In general, seismic monitoring should be provided and kept active on and around large dam sites, preceding by a couple of years the impounding of the storage reservoir in question.

As a general guideline, if significant movement along a fault crossing the dam site is accepted as a reasonable possibility during the lifetime of the dam, the best advice is to select an alternative site, less exposed to geodynamic hazard. Such standpoint is supported by the fact that no dam, foreseen to successfully survive the shearing action of a fault slip in its foundations, has ever been exposed to actual test under such event.

Due to the cumulative nature of fault movements and due to the vulnerability of dams to foundation movements, conservative estimates of the maximum possible fault movements are necessary for design and safety checks.

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