IMPLICATIONS OF COMPLEX SEISMOTECTONIC SITE CONDITIONS ON SEISMIC DESIGN OF LARGE DAMS

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ABSTRACT

The implications of complicated seismotectonic site conditions on the selection of the dam type and the seismic design are discussed. As a case study the proposed Rudbar Lorestan dam in Iran is used. The dam is located at a distance of ca. 1.6 km from an active fault, which is capable to produce earthquakes with a maximum magnitude of up to 7.5. The site is at a narrow gorge with almost vertical abutments and there are several faults and other discontinuities in the footprint of the dam, which can experience movements during strong earthquakes. The discontinuities (old faults, joints, bedding planes etc.) in the dam foundation are short and are not seismogenic. The following dam types are discussed: RCC gravity dam, earth core rockfill dam, and concrete-face rockfill dam. Due to the topography a concrete dam would be the obvious solution. For sites with active faults embankment dams are recommended by ICOLD. At such a site, foundation movements acting at several discontinuities and ground shaking act together. The peak ground acceleration of the horizontal component of the safety evaluation earthquake at the dam site is estimated as 0.7 g. Fault movements in the footprint of a dam are probably the most severe conditions a large dam may experience and may cause severe cracking in concrete dams. Therefore, the seismic analysis must be carried out for the cracked dam, which is a difficult task.

KEYWORDS: Concrete dam, embankment dam, fault movement, dam foundation, seismic design of dams

1. INTRODUCTION

The seismic hazard is the most severe hazard from the natural environment to be considered in the design of large dam projects located in areas of high seismicity. The earthquake hazard is a multiple hazard as besides ground shaking, earthquakes can cause (i) displacements along potentially active faults in the dam foundation, (ii) fault movements in the reservoir, resulting in the loss of freeboard and/or may generate water waves in the reservoir, and (iii) they can trigger landslides and rock falls into the reservoir, causing impulsive waves, etc.
It is also a well-known fact that the earthquake hazard is one of the least known hazards. Especially the estimate of the ground motion at the dam site for the strongest earthquakes with a very low probability of occurrence is difficult and associated with large uncertainties. Therefore, a thorough investigation is needed for the estimate of the ground motion of the different design earthquakes.
This paper gives an overview on the geologic and seismotectonic settings of the dam site, and the design aspects of dams, which can cope with both severe earthquake ground shaking and displacements in the footprint of the dam. Due to the vulnerability of concrete dams and especially arch dams to displacements along discontinuities in the dam foundation, the main concern of the seismotectonic study is related to the identification and assessment of movements in the dam foundation during strong earthquakes. The presence of active faults and the possibility of movements along discontinuities in the footprint of the dam during strong earthquakes may have severe consequences on the selection of the dam type and the dam site.
Moreover, due to its size and location in a highly tectonically stressed region with numerous faults, reservoir-triggered seismicity (RTS) caused by the filling and/or operation of the reservoir is quite likely. Although, this may not be a direct concern for the safety of a well-designed dam and appurtenant structures, RTS can still trigger mass movements into the reservoir, damage buildings and infrastructure, which have not

been designed against earthquakes, and may cause safety concerns of the population in the downstream valley. These psychological concerns have to be taken seriously. Thus, at such sites a seismic monitoring system must be installed in the dam and reservoir region prior to the construction of the dam. This system must then be operated for several years and shall cover the construction period, as well as the phases of filling and operation of the reservoir.
The present paper is mainly concerned with the multiple earthquake hazard of the proposed Rudbar Lorestan Hydropower Project located in the Zagros Mountain Range in Iran, a tectonically very active region.

2. DISCUSSION OF SEISMOTECTONICS OF RUDBAR LORESTAN DAM SITE

The Rudbar Lorestan dam project is located within the Zagros fold and thrust belt in the south of Aligudarz city in Iran. The height of the proposed dam is 158 m and the reservoir volume is about 200 million m^3.
The geologic and seismotectonic setting can be summarized as follows:

1. The dam site is located within a narrow valley with very steep walls. Dolomites of Dalan formation (late Permian) have formed both valley walls (Fig. 1).
2. The most important and closest active structure to the Rudbar Lorestan dam site is the Saravand-Baznavid fault (SBF), a segment of the Zagros Main Recent Fault (ZMRF). The ZMRF is a Quaternary right-lateral fault located between the southwestern part of Central Iran and the northeastern part of the Zagros active folded belt, in the west of the country. The ZMRF is a structure formed by a succession of individual fault segments. The horizontal slip rate along this fault is estimated at 10 - 17 mm per year.
3. The SBF with a length of ca. 100 km is an active fault. It is located along the Dorud fault (a segment of the ZMRF), which was ruptured during the January 23, 1909 Silakhor earthquake (Ms 7.4).
4. SBF is located at a distance of about 1.6 km from the proposed Rudbar Lorestan dam site.
5. The most important seismotectonic feature visible at the dam site is the F1 fault. This strike-slip fault is located in the left abutment and has the direction of the river. Dip of the fault plane is nearly 90° and the maximum fault offset is about 6 m. This fault with a length of less than 1 km is not a seismogenic fault. An adit excavated perpendicular to the F1 fault has shown that there are several parallel faults within a distance of 10 m. Reliable dating of the most recent fault movements was not possible.
6. Another fault is located in the right abutment originally called F10. In spite of features similar to those of F1 fault, it was concluded in an early project phase that this fault was a joint.
7. There are numerous other faults and discontinuities (old faults, joints, bedding planes, etc.) at the dam site, which have different orientations.

Figure 1: Rudbar Lorestan dam site in Iran: View from downstream to narrow gorge of dam site (left) and fault surface (F1) perpendicular to dam axis at left abutment during excavation of access road (right)

Several seismotectonic investigations were performed by different international and local experts. As the seismotectonic conditions at the dam site are very complex, different interpretations of possible movements in the footprint of the dam were presented. As fault movements in the footprint of dams have direct implications on dam safety, the optimum dam type had to be reviewed based on the seismotectonic assessments presented by the seismotectonic experts.

The following is a brief summary of the history of the seismotectonic assessment of the dam site and the resulting changes in the dam type:

- The narrow valley with an aspect ratio of crest length to dam height of about 1 and the good rock properties at the site were the main factors for the original consultants to propose an arch dam. At that time it was assumed that the dam site is stable.
- Further site investigations and the construction of an access road, which showed the F1 fault at the left abutment (Fig. 1), called for an updated study on the dam type. At that time it was concluded that F1 was active (and F10 was a joint) and that horizontal movements up to 0.50 m could occur in a single event along this fault. It was also assumed that the maximum fault width was less than 0.5 m. For the design of the dam a seismotectonic model was specified in which the two abutments can move relatively to each other along fault F1. A comparison of different dam types (arch-gravity dam, gravity dam, embankment dam) has shown that an RCC gravity dam with a slip joint at the left abutment would be the most economical solution. As a reference project the Clyde gravity dam in New Zealand, which also has a slip joint, was used.
- The additional seismotectonic investigations carried out in connection with the review of the RCC gravity dam with a slip joint clearly indicated that the seismotectonic model used was too optimistic as important features such as the blocky structure of the relatively brittle rock in the footprint of the dam, which was formed by different types of discontinuities (old faults, bedding planes, joints etc.), and also the width of fault F1of at least 10 m, were not taken into account. It is now assumed that movements can occur along several of the discontinuities in the footprint of the dam during a very strong earthquake at the SBF located close to the dam site. Therefore, the proposed slip joint of the RCC gravity dam would no longer be feasible as other joints would have to be added and since it is not possible to prevent movements at the discontinuities by structural means. It was also assumed that it will be extremely difficult to predict the maximum displacements, which could occur along the discontinuities in the footprint of the dam. Based on these changes in the basic seismotectonic design assumptions (design criteria for fault movements), there is a need for further clarification on the optimum dam type.

The seismotectonic situation at the Rudbar Lorestan dam site is such that it cannot be predicted reliably what will happen during a very strong earthquake at the nearby SBF. The dam site is unique as any other dam site, however, the special features of the site and their implications on the selection of the dam type calls for additional investigations and studies.

In international guidelines (ICOLD, 1998) the following statements related to a dam with potentially active faults in its foundation can be found:

- “Recognizing and accepting the existence of a capable fault in the dam foundation requires drastic steps. The site should preferably be abandoned in favour of a tectonically more stable one.“
- “There are cases when it is not possible to find a tectonically more reliable site. In such cases, concrete dams should preferably be eliminated as an advisable choice and an embankment dam with conservative features is to be considered.”
- “Situation may develop when fault activity potential of a dam site is uncertain and the geologist in charge cannot make decisive conclusions as to the capability of the foundation fault. Then the dam engineer must formulate the decision considering all the issues. But a general rule in such situations is to lean towards the side of safety because the nature of the problem requires quite a conservative approach.”
- “While special joints in concrete dams can be introduced with a measure of confidence in cases when a well defined fault movement is expected, still it remains rather a mitigating feature which might turn quite ineffective if some unexpected kind of movement intervenes.”

- "To date, no dam that was designed to absorb the fault movement has ever been put through the test. Thus the main validation criterion in our designs, the successful performance, is utterly lacking in this case."

These statements are quite clear as far as the dam type is concerned, i.e. an embankment dam with impervious core; and there are also doubts about the reliability of slip joints in concrete gravity dams. However, the knowledge about the seismotectonic situation at the Rudbar Lorestan dam site is still limited and therefore, allows different interpretations by different experts. Moreover, there are other non safety related criteria such as project costs, contractual obligations, availability of construction materials, time schedule, preferences in dam type etc., which have an impact on the optimum dam type, although the ultimate goal is to get a safe dam.

3. DISCUSSION OF OPTIMUM DAM TYPE

As pointed out earlier the dam will be located in a narrow gorge with good quality rock, which favours concrete dams. However, in view of the uncertainties with respect to possible movements in the footprint of the dam an embankment dam would be the preferred solution. Relatively few embankment dams have been constructed in a narrow gorge such as Rudbar Lorestan (Table 1); however, conceptual studies have shown that embankment dams are feasible for this site. The following types of embankment dams can be considered:

1. Earth core rockfill dam (ECRD);
2. Asphalt core rockfill dam (ACRD); and
3. Concrete face rockfill dam (CFRD).

The main item needed as a basis for the selection of the dam type is the seismotectonic design criteria. If displacements along discontinuities in the footprint of the dam are small (in the range of few centimetres) then any type of embankment dam is safe and even concrete gravity dams could be considered. However, for the Rudbar Lorestan dam site, where earthquakes with a magnitude up to 7.5 are possible at very close distance, displacements at the discontinuities in the footprint of the dam can be much larger. Earlier studies have assumed maximum movements of fault F1 in the range of 30 - 50 cm and more recent estimates have given a value of at least 100 cm in a single event. Besides these numbers no other information is available on displacements. Therefore, it is prudent to assume movements along discontinuities in the range of several decimetres. This will automatically exclude concrete dams at this narrow site when more than one discontinuity is crossing the footprint of the dam as it will not be feasible to design any concrete dam with more than one slip joint.

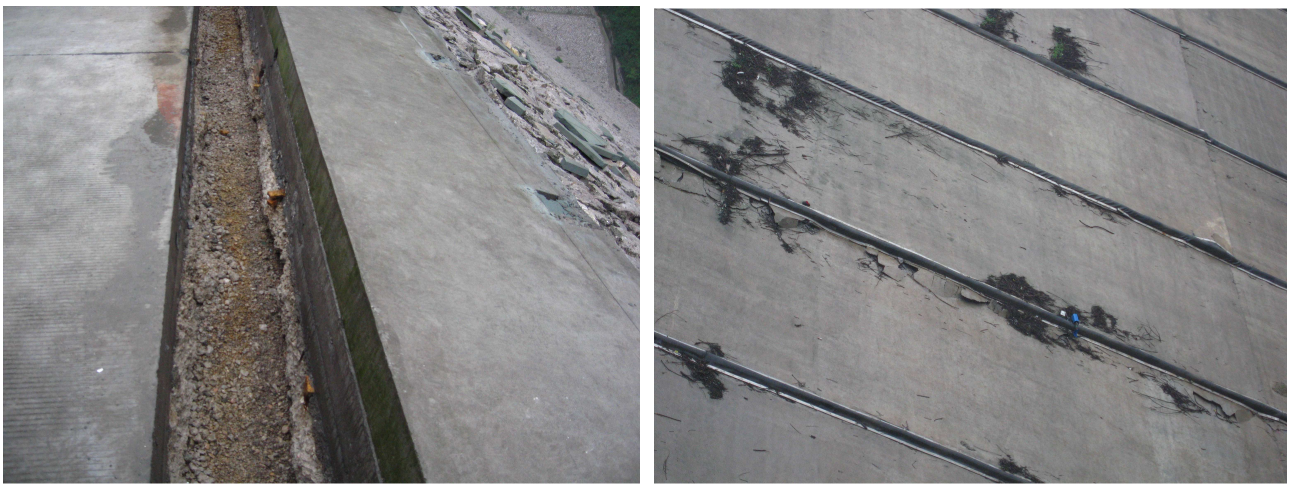

Fig. 2: Damage of Zipingpu concrete face rockfill dam caused by the magnitude 8 Wenchuan earthquake in China (May 12, 2008): Joint opening at crest (left) and spalling of concrete along joints of face slab (right)

Today RCC and CFRD dams are 'in'. They represent the state-of-the-art of dam construction. However, one disadvantage is that hardly any of these relatively new dam types has been exposed to strong ground shaking and even less is known about their behaviour under fault movements. Important results are expected from the observations and studies made after the May 12, 2008 Wenchuan earthquake in China, where the 156 m high Zipingpu CFRD (epicentral distance: 17 km) and the 132 m high Shapai RCC arch dam (epicentral distance: 12 km) were subjected to very strong ground shaking. Figure 2 shows some typical damage observed at Zipingpu CFRD.

In Sections 4 to 6 the seismic performance of CFRDs, RCC dams, and ECRDs is discussed when subjected to strong ground shaking. A detailed discussion on the vulnerability of different dam types to fault movements and design solutions are given by Wieland et al. (2008a, 2008b).

ACRDs may also be feasible and due to the inherent flexibility of asphalt the vulnerability of the asphalt core to in-plane stresses may be much less than that of the relatively rigid concrete face under seismic action. In the case of fault movements the thickness of the asphalt core must be widened so that the watertightness after a strong earthquake causing movements at discontinuities can be guaranteed. However, as experience with the seismic behaviour of ACRDs is very limited, more efforts have to be undertaken to study the seismic behaviour of these dams. Bottom outlets will be needed to lower the reservoir especially for dams which are vulnerable to seismic action.

In the dynamic analysis of the dam it can be assumed that fault movements and ground shaking can be separated, i.e. in the first step the deformations and cracks caused by fault movements or movements along discontinuities are determined; in the second step the ground shaking is then applied to the dam, which was deformed or cracked by fault movement.

4. SEISMIC ASPECTS OF CONCRETE FACE ROCKFILL DAMS

The seismic safety of CFRDs is often assumed to be superior to that of conventional rockfill dams with impervious core. However, the crucial element in CFRDs is the behaviour and performance of the concrete slab during and after an earthquake.

The settlements of a CFRD caused by very strong earthquakes are rather difficult to predict and depend on the type of rockfill and the compaction of the rockfill during dam construction. Depending on the valley section, the dam deformations will also be non-uniform along the upstream face, causing differential support movements of the concrete face, local buckling in compression zones etc.

In many cases, CFRDs are analysed with the equivalent linear method using a two-dimensional model of the highest dam section. In such a seismic analysis, relatively small dynamic stresses in the concrete face are calculated. These simple dam models have to be complemented by models, which also include the cross-canyon component of the earthquake ground motion as well as the inelastic deformations of the dam body. For such a dynamic analysis, a three-dimensional dam model has to be used and the interface between the concrete face and the soil transition zones must be modelled properly.

Due to the fact that the deformational behaviour of the concrete slab, which acts as a rigid diaphragm for vibrations in cross-canyon direction, is very different from that of the rockfill and transition zone material; the cross-canyon response of the rockfill may be restrained by the relatively rigid concrete slab. This may result in high in-plane stresses in the concrete slab. The seismic forces that can be transferred from the rockfill to the concrete slab are limited by the friction forces between the transition zone of the rockfill and the concrete slab. Due to the fact that the whole water load is supported by the concrete slab, these friction forces are quite high and, therefore, the in-plane stresses in the concrete slab may be sufficiently large to cause local buckling, shearing off of the slab along the joints or to damage the plinth, if the vertical joints do not allow for enough movements (Fig. 2).

Until recently this was still a hypothetical scenario, which seems to have been confirmed in the case of the Zipingpu CFRD (Fig. 2). It is necessary to look carefully into the behaviour of the concrete face under the cross-canyon component of the earthquake ground shaking. Up to now the seismic safety of concrete faces to cross-canyon motions has been largely ignored. Therefore, it is also not so obvious that CFRDs are more suitable to cope with strong earthquakes than conventional embankment dams. The main advantage with CFRDs is their resistance to erosion if water seeps through a cracked face. If the material zone below the slab is properly graded, it will not be eroded. This eliminates the possibility of large leaks developing underneath the cracked slab.

As a defensive measure to limit the effect of cracking, generous filter and transition zones have to be provided, which satisfy modern filter criteria (e.g., to have 35 to 40% sand with fines in the finest transition zone).
The damage of the concrete face of the Zipingpu CFRD caused by the May 12, 2008 Wenchuan earthquake in China clearly demonstrated that CFRDs may be vulnerable to strong ground shaking (Fig. 2). It is assumed that they are also vulnerable to movements along discontinuities in the dam foundation. As experience with the seismic behaviour of CFRDs is still very limited, more efforts have to be undertaken to study the seismic behaviour of these dams.

5. SEISMIC ASPECTS OF ROLLER COMPACTED CONCRETE DAMS

Most roller compacted concrete (RCC) dams are gravity dams and, therefore, their earthquake behaviour is similar to that of conventional gravity dams. High seismic stresses occur in the central upper portion of gravity and arch-gravity dams.
The main difference between RCC and conventional gravity dams is the dynamic behaviour of mass concrete. In RCC dams, the tensile strength in a lift joint may be a fraction of that of the parent mass concrete. This means that in case of a strong earthquake, horizontal cracks are likely to form along these interfaces. Besides, there will also be opening of vertical contraction joints. As gravity dams are designed to carry the loads by cantilever action and not by arch action, the formation of vertical cracks, or the opening of contraction joints is not a critical safety issue.
It has to be assumed that horizontal cracks extend from the upstream to the downstream face of a dam and thus completely separate the upper portion of the dam from the remaining part. Such cracks protect the remaining dam parts from further stresses. Also, the dam deformations will be mainly due to crack opening. Thus the post-cracking dynamic behaviour of concrete blocks separated by cracks or joints can be modelled by relatively simple rigid body models.
The concrete blocks are allowed to slide along the crack surface and to undergo rocking motions. It is the cumulative sliding motion, which governs the dynamic stability of detached blocks. The dynamic overturning stability is less of a problem as the rocking motion of a detached concrete block is generally a reversible process. Because of the large thickness of gravity dams, a sliding movement of several meters may be needed before a detached concrete block will fall down. Post-earthquake stability analyses are required considering uplift pressure along the sliding surface.
The cracking pattern in an RCC dam may be quite similar to that observed in the upper portion of the 106 m high Sefid Rud buttress dam, which was severely damaged during the June 21, 1990 earthquake in the northwestern part of Iran. There, the main cracks developed at the horizontal lift joints, which were not properly cleaned before concreting of subsequent lifts and thus exhibited relatively small shearing and tensile resistance.
Once cracks develop, it may be assumed that the full hydrostatic uplift pressure acts in this crack, leading to a further reduction of the shear resistance of the cracked lift joint as compared to the uncracked dam. For post-earthquake stability analyses full hydrostatic pressure should be considered.
From the point of view of dynamic stability of concrete blocks separated by cracks and joints, horizontal cracking planes of RCC dams are more favourable than inclined cracks.
In several RCC dams “bedding mortar” or “bedding mix” has been placed on lift surfaces, which increase the tensile strength. This special treatment prevents cracking and leakage under the more frequent moderate earthquakes. The bedding mortar has been placed on all lift joints, not just in the upper parts of dams.
Based on a qualitative assessment, it can be concluded that the seismic safety of RCC dams under strong ground shaking is most probably satisfactory, as cracks in the highly stressed central upper portion of the dam will develop along the horizontal construction interfaces. This is favourable for the dynamic stability of detached concrete blocks during strong ground shaking. However, further studies and observational evidence are needed to support this conclusion.

6. EARTHQUAKE DESIGN ASPECTS OF EARTH CORE ROCKFILL DAMS

The seismic performance of most earth core rockfill dams has been satisfactory. The only dams that have been

known to fail completely as a result of seismic shaking were tailings or hydraulic fill dams, or relatively small earthfill embankments of older and, perhaps, inadequate design and construction.
The main recommendations for design and construction of embankment dams subject to severe earthquake shaking are as follows (ICOLD, 2001):

- Foundations must be excavated to very dense materials or rock; alternatively the loose foundation materials must be densified, or removed and replaced with highly compacted materials, to guard against liquefaction or strength loss.
- Fill materials, which tend to build up significant pore water pressures during strong shaking must not be used.
- All zones of the embankment must be thoroughly compacted to prevent excessive settlement during an earthquake.
- All embankment dams, and especially homogeneous dams, must have high capacity internal drainage zones to intercept seepage from any transverse cracking caused by earthquakes, and to assure that embankment zones designed to be unsaturated remain so after any event that may have led to cracking.
- Filters must be provided on fractured foundation rock to preclude piping of embankment into the foundation.
- Wide filter and drain zones must be used.
- The upstream and/or downstream transition zones should be self-healing, and of such gradation as to also heal cracking within the core.
- Sufficient freeboard should be provided in order to cover the settlement likely to occur during the earthquake and possible water waves in the reservoir due to mass movements etc.
- Since cracking of the crest is possible, the crest width should be wider than normal to produce longer seepage paths through any transverse cracks that may develop during earthquakes.

The design of defensive measures for embankment dams with potentially active faults in their foundation is discussed by Wieland et al. (2008b).

7. EMBANKMENT DAMS IN NARROW CANYONS

High embankment dams in narrow valleys are still a controversial issue although there are several examples of such projects with satisfactorily performing dams. The most significant projects with length to height ratios less than about 1.5 are listed in Table 1. In the subsequent Sections the main concerns usually discussed among experts advocating or opposing such dams are briefly discussed, i.e. (i) stress relief features inside the abutments; (ii) arching and hydraulic fracturing; (iii) movements along the abutments; and (iv) sloping versus vertical core.

Table 1: Examples of existing high embankment dams in narrow valleys

Name	Year of Completion	Dam Height, H (m)	Crest Length, L (m)	L/H	Type of Dam	Type of Sealing Element	Valley Shape
Chivor, Colombia	1975	237	310	1.30	ECRD	Sloping core	V
Golillas, Colombia	1978	120	110	0.92	CFRD	Concrete face	V
Chicoasén, Mexico	1980	240	306	1.28	ECRD	Vertical core	U
Guavio, Colombia	1989	247	380	1.54	ECRD	Sloping core	V/U

7.1 Stress relief features

Abutments often exhibit features indicating stress relief caused by the absence of the lateral stress when the valley became subject to erosion. The stress relief features are more or less parallel to the slopes of the valley. The steeper the valley walls the more pronounced will be the relief features. Detrimental consequences of the stress relief are open joints or also more or less uniformly loosened zones parallel to the valley slopes.
Ideally, the loosened zones should be removed below the area of contact with the core but this can be

technically impractical and uneconomical. Hence, these zones must be treated by consolidation grouting. However, complete watertightening may not be feasible and there remains a risk of piping through the material filling the joints which could not be reached by the grouting work. It is therefore essential that filters also cover the abutment beyond the core.

7.2 Arching and hydraulic fracturing

All earth cores in embankment dams are susceptible to cracking and most cores are believed to have cracks even these are usually hidden by the dam's shells and therefore not visible. The most detrimental form of cracking is transversal cracking usually caused by tensile stresses which develop as a result of differential settlement of the core zone or because of materials of different stiffness in the foundation. Differential settlements may develop along steep abutments. This phenomenon is particularly critical in the upper part of the dam where the vertical stress is low and unable to oppose tensile cracking. In addition, seepage paths are short. Arching, both in transversal and longitudinal direction, can produce stress conditions which are prone to hydraulic fracturing. Such conditions can occur as a result of arching of a narrow vertical core between two rigid steep flanks of a valley. The most efficient way to mitigate the hazard of hydraulic fracturing is to provide a fully intercepting system of filters and drains, designed very conservatively. The arching effect is very sensitive to the shape of the valley, even in the case of very narrow conditions.

7.3 Movement along the abutments

The interaction between core and abutment rock is still a controversial issue. Some experts argue that there should be no slippage between core and abutment with correspondingly rough rock contacts, while others promote the preparation of smooth contact surfaces facilitating movement along the abutment. Movement along abutments is however a fact that has been verified by measurements.

7.4 Sloping versus vertical core

In very narrow valleys sloping cores are usually preferred, especially with high dams. The weight of the upstream shell on the core tends to reduce the arching and therefore increases the compressive stresses in the core, which is essential to diminish the possibility of crack development or hydraulic fracturing.

8. CONCLUSIONS

At sites where movements along discontinuities (faults, joints, bedding planes etc.) in the footprint of the dam are possible during strong earthquakes a flexible embankment dam, such as a well-designed earth core rockfill dam, is the safest option. This is the case when an important fault capable of large earthquakes and surface breakage is passing a dam site within a distance of a few kilometres and when the rock formations at the dam site may experience movements along pre-existing discontinuities in the footprint of the dam. Although, such sites should be avoided whenever possible, this may not be a feasible option in regions of high seismicity such as the Zagros Mountain Range. However, the proximity of important faults may have direct implications on the available dam options. An issue, which has been largely ignored up to now.

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