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CFRDs in highly seismic regions

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Until the Wenchuan earthquake of 12 May 2008 no large concrete face rockfill dam (CFRD) was subjected to strong ground shaking. Quite a few dam engineers were of the opinion that CFRDs are inherently safe against earthquakes, because any leakage in the concrete face would not lead to the failure of the dam. Even if such a state could be achieved excessive leakage could not be tolerated and the reservoir would have to be drawn down if severe damage of the concrete face and/or the water proofing system has to be assumed. In this paper the main measures to be considered to achieve a safe CFRD in highly seismic regions are discussed

In the last twenty years concrete face rockfill dams (CFRDs) have been built in increasing number. However, because the number of these dams is still relatively small, experience on the actual performance of these dams under strong earthquake loading is still very limited. We have to realize that not all seismic problems pertaining to large dams have been solved. Every time there is another strong earthquake, upgrading the design criteria and design concepts may become necessary. This applies in particular to more recent types of structures such as CFRDs.

In the subsequent sections some of the relevant earthquake aspects of CFRDs are briefly discussed. Before an attempt is made to solve a particular problem, it is important to take an integral look at the phenomenon first, otherwise important aspects may be overlooked. This is particularly true for new types of dams.

An overview on the seismic aspects of CFRDs is given in the General Report on seismic aspects of dams presented at the 21st ICOLD Congress (Wieland, 2003). At that time, the information on the performance of CFRDs under seismic loading was still very scarce.

The study of the damage of the concrete face of Zipingpu CFRD in China caused by the Wenchuan earthquake will have implications on the seismic design of high CFRDs in highly seismic regions. At the moment the world's highest CFRD, Shuibuya dam in China, has a height of 233m and it is planned to use this technology for dams with heights up to 300m. Before such dams can be built a more thorough understanding of the behaviour and safety of CFRDs under strong earthquake ground shaking is needed. This can be achieved by sophisticated dynamic analyses, shaking table tests, and strong motion instrumentation will eventually provide useful data. In the past the earthquake vulnerability of CFRDs was assumed to be lesser than that of other dam types; however, today this opinion is questioned as the seismic hazard is a multiple hazard, which, depending on the site, does not only include ground shaking but also fault movements, rockfalls and others.

Behaviour of Zipingpu CFRD

The 156m high Zipingpu CFRD is one of the largest CFRDs in China and one of the key projects for water supply and irrigation for the Chengdu basin. The dam was completed in 2006 and represented the latest CFRD technology in China. The dam was designed for an intensity of VIII (Chinese scale), with a design peak ground acceleration of 0.26 g.

The dam was subjected to very strong ground shaking during the 12 May 2008 Wenchuan earthquake (magnitude 8.0). The dam was located 17km from the earthquake epicenter in Wenchuan County. The intensity in the epicentral region was XI and at the dam site in the range of IX to X. This intensity is far beyond the value accepted in the original design. During the earthquake the reservoir level was low and its volume was 300Mm^3. Under normal operation conditions the reservoir volume is 1100Mm^3. The crest of the dam and the concrete face were damaged. A description of the Wenchuan earthquake and the damage to large dams and the Zipingpu CFRD was published by Chen H. (2008), Chen S. (2008), and Xu (2008). From the six strong motion instruments installed in the dam only the three located on the crest provided data, the other instruments were out of order during the earthquake. On the crest, the recorded peak accelerations were over 2g; however, as the concrete structure of the crest behaved differently from the dam body and since the concrete part also separated from the rockfill, the dynamic behaviour of the concrete elements of the crest was quite different from that of the rockfill. This was reflected in the high frequency components of the accelerograms recorded by the instruments, which were attached to the concrete elements on the crest.

Of greatest interest was the damage to the concrete face and waterproofing system which consisted of damage of the vertical joints and the offset of the horizontal joint between the second and third stage slab construction (Figures 1 to 3).

After the earthquake the maximum settlement at the dam crest was 735mm and the horizontal deflection in downstream direction was 180mm. The cross-canyon deformation of both abutments was 102mm. Because of the low water level in the reservoir at the time of the earthquake, it is difficult to estimate what the earthquake behaviour of the dam, the concrete face, and the waterproofing system would have been if the reservoir were full.

Zipingpu dam will be a milestone in the development of CFRDs. The lessons and experience from this project will provide an excellent reference for dam engineers in seismic areas of the world.

The damage observed at Zipingpu CFRD is acceptable for very strong ground shaking such as the safety evaluation earthquake (SEE). Besides the satisfactory behaviour of the dam, it has to be pointed out that bottom outlets and spillway gates must be operable after the SEE, i.e. the performance criteria applicable to these components are stricter than those for the dam where according to ICOLD guidelines (ICOLD, 1989) structural damage is accepted as long as the dam is stable and no uncontrolled release of water takes place that would lead to catastrophic flooding in the downstream area.

General seismic features of CFRDs

Since the rockfill is essentially dry, earthquake shaking cannot generate excess pore water pressures. With the absence of pore water pressures and the high shear strength of compacted rockfill, this dam type is considered inherently resistant to seismic loading (Cooke, 1991). Possible failure modes that were considered are (1) sliding of shallow material along planar or nearly planar surfaces and (2) wedge failure or deep-seated rotational failure (Seed et al., 1985).

However, there are certain features with these dams, which should not be overlooked (Wieland and Brenner, 2008):

• a) Vulnerability of perimetric joint: The perimetric joint connecting face slab and plinth is a critical element in the dam. It is protected with filters, thus the washing out of foundation material can be prevented in the case of leakage.

• b) Crack development in the concrete face slab: Due to deformations in the rockfill the concrete face slab will experience cracking. By properly compacting rockfill deformations can be minimised as well as crack development. Zones in the upstream part of the embankment in particular, including fine and coarse-grained transition zones under the slab, should be constructed of material of low compressibility.

• c) Deformations in CFRDs: The long-term settlement of well compacted rockfill is in the range of about 0.1 to 0.2 % of the dam height. Strong ground shaking can produce settlements in the order of 0.5 to 1m.

Seismic behaviour and seismic safety aspects

The 85m high Cogoti CFRD in Chile (Figure 5), completed in 1938, has been shaken by several earthquakes (Arrau et al., 1985). The 1943 Illapel earthquake with a magnitude of 7.9 and an epicentral distance of about 90km produced a peak ground acceleration (PGA) of 0.2g and a crest settlement of 38cm. This dam was constructed of dumped rockfill without any water sluicing. There was no damage to the face slab which had a thickness varying from 80cm at the base to 20cm at the top. The earthquake produced an instantaneous settlement of the crest of 40cm. Leakage increased from 200l/sec to 1400l/sec after the earthquake and, today, after repair it decreased to 400l/sec.

On 14 October 1997 the magnitude 6.8 Punitaqui earthquake with epicentral distance of 20km and focal depth of 30km produced a PGA of 0.19g and a crest settlement of 15cm (Figure 5). No damage was reported from the concrete face.

A 17m high CFRD saddle dam on the right abutment of Sugesawa dam (Figure 6) in Japan was shaken by the 6 October 2000 Tottori earthquake. The PGA measured on the right abutment of the saddle dam was 0.36g. No damage was observed (Matsumoto et al., 2001).

During the Iwate-Miyagi Nairiku earthquake of 14 June 2008 in Japan (JMA magnitude 7.2) the 53m high Ishibuchi CFRD was subjected to very strong ground shaking with a PGA of 1.04g at the base. However, the recorded peak crest acceleration was only 0.54g. The epicentral distance was 16km. The dam was built in 1953 and was made of dumped rock similar to Cogoti CFRD. The dam settled 60cm during the earthquake, whereas the long-term settlements from 1953 to 2008 were 50cm. No damage was observed at the concrete face. This is due to the fact that the concrete face rotated along the base when the dam settled.

These case histories are from regions of high seismicity and depending on the location of major CFRDs relative to geologic structures much higher ground motions can be expected at sites of high dams. CFRDs are different from conventional rockfill dams because (1) the concrete face is a much stiffer element than the compacted rockfill zones, and (2) the concrete slab is impervious and acted upon by the hydrostatic pressure, causing high compressive stresses on the rockfill particles in the lower part of the face zones. Therefore, upstream slope stability is ignored in analyses.

Earthquake analyses of CFRDs in the past have focussed mainly on settlement predictions of the crest and deformations of the dam body and the stability of the downstream slope. Numerical analyses mostly employed two-dimensional models and methods included simplified procedures. For well-designed and well-compacted CFRDs, the use of simplified procedures or the equivalent linear analysis, in combination with Newmark's sliding block analysis of slopes, is used by dam designers.

Little attention has been paid to the seismic behaviour of the face slab although it is generally agreed that during a strong earthquake the face slab is likely to crack. Since cracks in the slab and leakage are accepted as they are not safety relevant in the case of well-designed CFRDs there has been little interest in sophisticated seismic analysis of the rockfill/slab system.

For the assessment of the seismic performance of the concrete slab of CFRDs, the analysis of the effect of the cross-canyon earthquake component is mandatory to arrive at realistic results. The deformational behaviour of the almost rigid concrete slab for in-plane motions is very different from that of the rockfill zones in the embankment, thus the motion of the rockfill in crest direction will be restrained by the face slab. Therefore, for cross-canyon vibration, the stiff concrete face will attract seismic (membrane) forces from the dam body. Hence, very high in-plane stresses may develop in the face slab. Shear failure and/or spalling of concrete may occur at the highly stressed joints. The existence of such forces can be seen from the buckling of precast elements used for the upstream slope protection of a levee in Taiwan (Figure 7).

It is concluded that the analysis of the cross-canyon earthquake effect be considered in the seismic analysis of CFRDs in order to clarify the magnitude of dynamic stresses in the face slab and the response of the slab to these forces. It is also recommended to supplement dam instrumentation with strong motion instruments, especially in regions of high seismicity and in large CFRDs.

The opening of vertical joints in the face slab during earthquake loading was studied by Harita et al. (2000) with a three-dimensional elastic finite element model which had non-linear spring elements at the slab joints. A loading history of about 10s duration and with a horizontal PGA of 0.18g produced a joint opening of about 15mm at the top of the slab. Joints repeatedly opened and closed during seismic loading and the slab movement followed that of the dam body.

Assessment of consequences of seismically damaged concrete face

The hydrostatic water pressure is pressing the concrete face on to the face support and transition zone materials. Thus the shear resistance against sliding of the concrete face on these materials is also growing with increasing water pressure. At the same time the water pressure prevents the separation of the concrete face from the soil. The damage patterns of a concrete face shown in Figures 1 to 5 are more likely to be expected in the uppermost parts of the dam. At greater water depth local joint damage in the concrete face due to compression and shear but also joint opening, must be expected, leading to increased leakage losses. Widening of existing cracks within the concrete slab elements should also to be expected all over the concrete face.

Due to the fact that in many concrete slabs the reinforcement is placed in the middle plane of the slab the flexural stiffness will reduce significantly once cracks have formed. Also the crack width will be larger at the surface as in the case where the reinforcement would be placed in two separate layers near the surfaces of the slab. Although a large concrete cover is needed from the durability point of view, standard reinforcement of the elastically supported slab elements would be beneficial. At the vertical joint additional reinforcement is needed to prevent spalling (high stresses normal to the joint surface) due to impacting slabs and for proper transfer of the shear forces.

After strong ground shaking, leakage is expected to increase significantly. It should be shown in the seismic design of the concrete face (as a worst case) that the complete failure of a slab element does not have a negative effect on the safety of the dam and that such a failure scenario can be accepted.

Seismic design features for CFRDs

For the design of a high CFRD in a highly seismic region the following measures are recommended, which improve the performance and the seismic safety of the dam:

• (1) Flat slopes (reduce seismic deformations).

• (2) Generous freeboard (accounts for seismic deformations and impulse waves in the reservoir).

• (3) Wide crest (improves safety of crest region of dam and increases resistance against overtopping from impulse waves).

• (4) Proper material selection in dam body with proper zoning (rockfill shall allow free draining of water leaking through the concrete face).

• (5) Provision of geogrid and other techniques for strengthening the downstream slope of the crest region of CFRD.

• (6) Provision of a bottom outlet (to lower the reservoir if the concrete face or waterproofing system is damaged).

• (7) Concrete panel with smaller width to account for non-uniform deformations of the concrete face.

• (8) Arrangement of reinforcement of the face slab to improve load bearing behaviour in-plane and out-of-plane and ductility.

• (9) Arrangement of proper joint system including horizontal joints and selection of the joint width to account for the reversible nature of the seismic response.

• (10) Water-proofing system of face slab and the plinth joint to account for static and seismic joint movements.

• (11) Well-compacted rockfill, etc.

Moreover, the general design features for embankment dams given in ICOLD Bulletin 120 (ICOLD, 2001) will contribute substantially to the satisfactory behaviour of a CFRD under strong ground shaking.

As joint leakage is accepted after the SEE, a different design earthquake may be specified for the water proofing system. In general, it is too conservative to design the water proofing system for the SEE. The dam must be designed for the SEE and it may experience inelastic deformations. The strictest seismic performance criteria are applied to the outlets (bottom outlet, spillway gates), which must be operable after the SEE.

Conclusions

Concrete face rockfill dams are economically attractive alternatives to conventional earth-core rockfill dams. Since there exist few observations about the response of these dams to strong earthquakes, their seismic performance must be studied carefully taking into account all existing information.

Well-designed and properly compacted CFRDs on rock foundations are expected to perform well during strong earthquake action. Despite, the information available from Zipingpu CFRD, the seismic behaviour of the concrete face under full reservoir condition must still be studied further. The large membrane forces in the face slab generated by the cross-canyon excitation may cause local buckling at the joints, rupturing of water stops and/or movements of individual slab elements as rigid body. If such movements will take place then the flow across the slab will greatly exceed the leakage through structural cracks in the concrete slab. The in-plane forces in the face slab are mainly governed by the joint system and the joint width. If the joints remain open during static and seismic actions then the in-plane forces will remain small. However, if the joint width is small then the parts of the concrete face under compression will behave like a monolithic slab and the compressive forces will become very large. This is a typical behaviour of structural elements subjected to deformations from shrinkage, creep, temperature effects, differential settlements, etc. Moreover, under seismic action the joint displacements will be oscillating and a compression joint may open and tension joints may close repeatedly.

It has to be expected that cracks in face slabs of existing CFRDs will be increased during seismic action.

The high mass and stiffness properties of concrete elements on the crest of CFRDs can lead to a separation of the crest structure from the dam body (rockfill). Thus the dynamic behaviour of the concrete elements at the crest may be different from the crest of a conventional earth-core rockfill dam.

The largest CFRDs under construction have heights exceeding 200m. Local damage of the concrete face (especially large joint displacements) due to earthquake action may drastically increase leakage losses. This has not been the case in the Zipingpu CFRD. For the safety of high CFRDs it is important to know if the consequences of joint leakage (with large leakage) have a negative effect on the safety of the dam.

The slopes of CFRDs in highly seismic areas should be rather flat as the crest deformations of the dam will be governed by the slopes and crest width as well as concrete elements on the crest.

It is recommended to perform thorough studies of the behaviour of Zipingpu CFRD for full reservoir condition by modelling (i) three-dimensional effects, (ii) the joints between slabs, (iii) the concrete elements at the crest, (iv) the interface between slabs and the curbs, and (v) the dynamic deformation behaviour of rockfill.

Although this paper only discusses the effect of ground shaking, CFRDs may be vulnerable to earthquake-triggered differential movements at discontinuities in the foundation of a dam.

Dr. Martin Wieland. Chairman, ICOLD Committee on Seismic Aspects of Dam Design, Poyry Energy Ltd., Hardturmstrasse 161, CH-8037 Zurich, Switzerland, martin.wieland@poyry.com

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