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EARTHQUAKE ASPECTS OF ROLLER COMPACTED CONCRETE AND CONCRETE-FACE ROCKFILL DAMS

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SUMMARY

Roller compacted concrete (RCC) dams and concrete-faced rockfill (CFR) dams have become viable alternatives to large conventional concrete and embankment dams because of their considerable potential economic benefits. These new dams create also new risks, as their seismic is not known properly. A qualitative assessment of the seismic performance of RCC and CFR dams under strong ground shaking is presented and possible problems and deficiencies are discussed. Accordingly, RCC dams are expected to behave quite similarly to conventional concrete dams, but in the case of CFR dams some aspects related to the concrete face have been identified, which need further investigation.

INTRODUCTION

In the last twenty years the following two new dam types have been have been built in increasing number:

(i) RCC (roller compacted concrete) dams; and

(ii) CFR (concrete-face rockfill) dams.

The reasons, which have lead to these new developments, were mainly of economic nature. However, because the number of these dams is still relatively small and since most of them were built within the last decade (many more projects are on the drawing boards – many of them in China), the experience with the earthquake behaviour of these dams is still very scarce. We have to realize that we have not yet solved all seismic problems of large dams. Every time there is another strong earthquake, we have to upgrade the design criteria and design concepts. This applies in particular to new types of structures such as RCC and CFR dams. But there is also very little experience with the seismic performance of grout curtains and diaphragm walls, which form an important part in any dam project.

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In the subsequent sections some of the relevant earthquake aspects of RCC and CFR dams are briefly discussed without going into the theoretical details of possible mathematical models. Before an attempt is made to solve a particular problem, it is important to have an integral look at the phenomenon first. Otherwise important aspects may be overlooked. This is particularly true for new types of dams.

A comprehensive overview on the seismic aspects of dams in including RCC and CFR dams is given in the General Report of the 21st ICOLD Congress (Wieland, 2003). The state-of-practice on earthquake safety of dams was discussed in some 75 reports. However, the information on seismic effects on RCC and CFR dams is still very scarce. Once experimental and/or observational information will become available, the current design practice may have to be reviewed.

GENERAL FEATURES OF ROLLER COMPACTED CONCRETE DAMS

RCC dams are mainly gravity dams, but this technology has also been used for some arch gravity dams with a vertical upstream face, i.e. single curvature arch dams. The stresses in gravity type of dams due to dead load and water load in the reservoir are relatively small in most parts of the dam. The highly stressed zones are confined to relatively thin layers at the up- and downstream faces and at the heel and toe of the dam, where local stress concentrations are present. This allows the use of concrete with a relatively low strength over most parts of the dams. Unfavourable tensile stresses, which are also confined to the up- and downstream surface layers, mainly in the upper portion of the dam, may be caused by earthquake action.

The main economic advantages result from the following features of RCC dams:

(i) **Speed of construction:** Large volumes of (low or high paste) concrete can easily be placed with heavy equipment, thus shortening the construction period of these dams.

(ii) **Low unit costs of RCC:** The unit cost of low paste mass concrete is favourable, to reduce the heat of hydration a significant portion of cement is usually replaced by locally available pozzolanic materials or fly ash.

(iii) **Incorporation of spillway into dam body:** Due to the slope of the downstream face of 1:0.8 (gravity dams) to 1:0.4 (arch-gravity dams), the spillway can directly be incorporated into the dam body. This is a major advantage for dams which have to accommodate large floods and which are in need of large spillways.

(iv) **Use of shape of conventional dams:** Because the stresses in gravity type dams are low, the cross-sections of RCC dams are the same as those of conventional dams.

Because of the above advantages, RCC dams are interesting alternatives to conventional dams in most parts of the world.

The main disadvantages are the following:

(i) **Watertightness:** Due to the construction of the dam in thin horizontal layers, in the case of high hydraulic gradients, water may percolate along the horizontal construction interfaces. Special measures may be needed at the upstream face of the dam to improve the watertightness, i.e. layer of high paste monolithic mass concrete or a surface sealing by a geomembrane.

(ii) **Limited experience of engineers and contractors:** Few designers and contractors have extensive experience with the design and construction of RCC dams. The design and construction practice are still in development.

(iii) **Limited experience with safety and long-term performance:** No large RCC dam has been exposed to extreme loadings like strong ground shaking during an earthquake or large floods.

(iv) **Galleries:** Placement of RCC around formwork, which is needed for access galleries in the dam body, is tedious and slows down the construction process.

The main weaknesses of RCC dams are the watertightness under high hydraulic gradients, ageing mechanisms and the unknown performance under seismic loading.

GENERAL FEATURES OF CONCRETE-FACE ROCKFILL DAMS

The CFR dams consist essentially of a zoned rockfill embankment sealed on the upstream side by a thin concrete slab. Transition and filter zones are provided in the zone beneath the concrete slab. The concrete face, together with the perimetric joint and the plinth, are the elements, which provide the watertightness of the dam above ground.

The main advantages of CFR dams as compared to conventional earth core rockfill dams may be summarized as follows:

(i) **Steep slopes:** The high friction angles achieved with compacted rock and gravel fills and the absence of an impervious zone with high pore water pressures during rapid drawdown, enables designing the dam body with steeper slopes. This reduces the volume of fill placement and thus the construction costs. The costs for concrete face construction may also be lower than those for filter and impervious core.

(ii) **Speed of construction:** Fill placement is relatively straightforward and independent of weather conditions. Compaction of the rockfill during rainfall is even advantageous as it reduces the need for wetting the material being placed. Fill placement can start before construction of the grout curtain is completed.

(iii) **Stabilizing effect of water load:** The resultant of the water load is transmitted into the foundation upstream of the dam axis.

(iv) **Economy:** Because of smaller fill volume a CFR dam is usually more economic than the earth core rock fill dam provided suitable rockfill material can be obtained in the vicinity of the dam.

(v) **Earthquake stability of rockfill:** 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 shall not be overlooked, i.e.

(i) **Vulnerability of perimetric joint:** The perimetric joint connecting face slab and plinth (or toe slab) is the most critical element in the dam. When it ruptures leakage will occur. However, by providing adequate filter zones the washing out of foundation material can be avoided.

(ii) **Crack development in the concrete face slab:** Due to deformations in the rockfill the concrete face slab will experience cracking. However, experience with existing dams has shown that properly compacted rockfill can minimize deformations and also crack development. Especially zones in the upstream part of the embankment, including fine and coarse-grained transition zones under the slab, should be constructed of material of low compressibility. The ideal material is alluvial gravel if available (Mori, 1999). With compacted gravel fills very high deformation moduli can be obtained.

(iii) **Deformations in CFR dams:** Experience with carefully monitored dams of compacted rockfill revealed that crest settlements are very small, i.e. in the range of about 0.1 to 0.2 % of the dam height and may essentially be completed within three to five years. Dams in narrow valleys can be affected by arching and the settlement process is delayed. Strong earthquake can produce further settlements. They are estimated to be of the order of 0.5 to 1.0 m. However, this magnitude of crest settlement is no problem to dam safety provided the dam has been designed with an adequate freeboard.

(iv) **Limited experience in design and construction:** Concrete face rock fill dams higher than about 30 m have been built since the early 1920s (Cooke, 1985). However, in those dams the rockfill was placed by dumping and consequently the fill was loose with a considerable potential for settlements upon shaking. Modern CFR dams with compacted rockfill became of interest in the late 1960s and by now there is a great number of such dams, especially in Brazil and China. But in many countries where dam construction is sporadic, contractors do not have the experience in building such a dam and in order to engage a local contractor another dam type may be chosen by the owner.

(v) **Aging of concrete face:** The concrete face is not a geomaterial and will be affected by aging processes much faster than earth and rockfill materials. The concrete face and the joints with waterstops between the slabs may need repair during the life time of the dam.

The above list demonstrates that CFR dams have special features which must be properly taken into account in a successful design. At the upstream toe of the dam there is a very high hydraulic gradient, usually roughly estimated as the water head divided by the width of the plinth. For foundation conditions on good quality (slightly weathered) non-erodible rock, this gradient can be as much as 20 whereas for plinth foundations on weathered rock, residual soil etc. the gradient should be reduced to about 10. Still these gradients are much higher than those recommended for earth core rockfill dams where the width of the core base should not be less than about one fourth of the water head. Similarly, modern arch dams have a base with a width not more than one fifth of the water head. Hence, gradients in CFRD dams are about 2 to 5 times higher than those in earth core rockfill or arch dams respectively, depending on the quality of the foundation material.

SEISMIC SAFETY ASPECTS OF ROLLER COMPACTED CONCRETE DAMS

RCC dams are essentially gravity type of dams and, therefore, their earthquake behaviour is very similar to that of conventional gravity dams. High seismic stresses occur in the central upper portion of gravity and arch dams.

The main difference of RCC to conventional dams is the dynamic behaviour of mass concrete. In the case of conventional mass concrete the material properties are isotropic within a concrete cantilever. In RCC dams the tensile strength in a lift joint may be a fraction of that of the isotropic mass concrete. This means, that in case of a strong earthquake horizontal cracks can form along any of these interfaces. Besides, there can also be opening of any vertical contraction joints. As gravity type 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 are not a critical issue.

The main safety concerns are the horizontal cracks. If a horizontal crack is formed, which is inclined towards the upstream face of an arch gravity dam then a detached concrete block may slide progressively into the reservoir during repeated earthquake shaking. The formation of cracks in a monolithic, isotropic dam is difficult to predict. Crack geometries and the approximate location of discrete cracks may have to be discussed based on fracture mechanics.

As a matter of fact, cracks and joint opening may not be detrimental to the earthquake safety of the dam. The 57 m high Lower Crystal Springs gravity dam, which is located very close to the San Andreas fault, survived the powerful 1906 San Francisco earthquake with no damage (Fig. 1). The dam is made of a large number of interlocking concrete blocks. The friction in the joints and the block interlock prevented joint movements. A similar mechanism is expected for concrete blocks in RCC dams separated by joints and horizontal cracks.

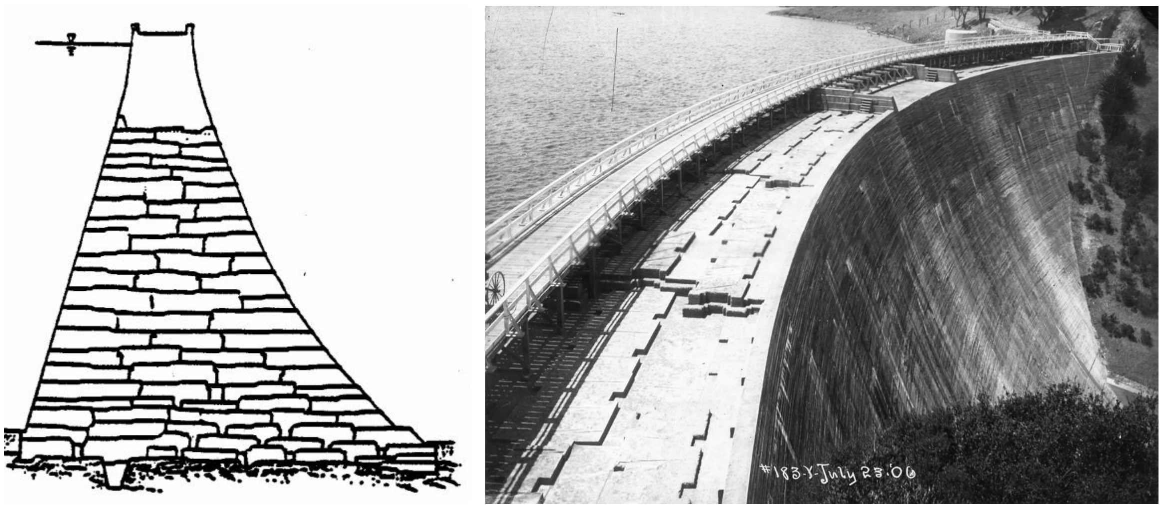

Fig. 1: Lower Crystal Springs gravity dam made of interlocking concrete blocks. The dam located close to the San Andreas fault was undamaged after having been shaken by the 1906 San Francisco earthquake (Photograph courtesy City of San Francisco)

It has to be assumed that cracks develop from the up- to the downstream face of a dam and thus separate the upper portion of the dam from the remaining part. Such cracks also relieve the remaining dam parts from further excessive stresses and the dam deformations will be mainly due to crack opening, i.e. 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 rock. It is the cumulative sliding motion along an inclined crack, which governs the dynamic stability of detached blocks. The dynamic overturning stability is less of a problem because the rocking motion of a detached concrete block is a reversible process. The friction and interlocking forces in the vertical contraction joints also prevent larger rocking motions in relatively slender concrete blocks. However, in RCC dams the geometry of any detached block is rather bulky. 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.

In conventional concrete dams cracks occur preferably along the horizontal lift joints, which are spaced at distances of two to three metres. Because of the staggered construction of the concrete blocks in some of the very large gravity dams, the lift joints are discontinuous, thus the orientation of the crack plane may not necessarily be horizontal.

In RCC dams the horizontal lift joints are at narrow spacing and cut through the whole dam section, thus during an earthquake very few completely horizontal cracks will form in the upper portion of the dam. The cracking pattern will be very similar to that observed in the upper portion of the 106 m high Sefid Rud buttress dam, which was severely damaged during the M_s 7.7 Manjil earthquake of June 21, 1990 in Northwestern Iran (Indermaur et al., 1991, Fig. 2). There, the horizontal cracks developed at the horizontal lift joints, which were not properly cleaned before concreting subsequent lifts. The ground motion at the dam site caused by the Manjil earthquake, which resulted in the loss of lives of ca. 40,000 people, many of them in the region of the Sefid Rud dam, was close to that, which would be expected to occur during an MCE. Thus this is one of the very important case studies to assess the behaviour of large concrete gravity dams under extreme ground shaking. It is important to note, that the detached concrete blocks did not move horizontally along the cracked lift joints. This was probably the result of high friction forces in the joints between adjacent buttresses. There were also no indications of inclined cracks at the upstream face of the dam. However, inclined cracks formed at the intersection of the buttress head and the web. These cracks were the result of a sudden change in the stiffness of the buttress in the top portion of the dam. However, this particular feature is not representative for a gravity or arch-gravity dam.

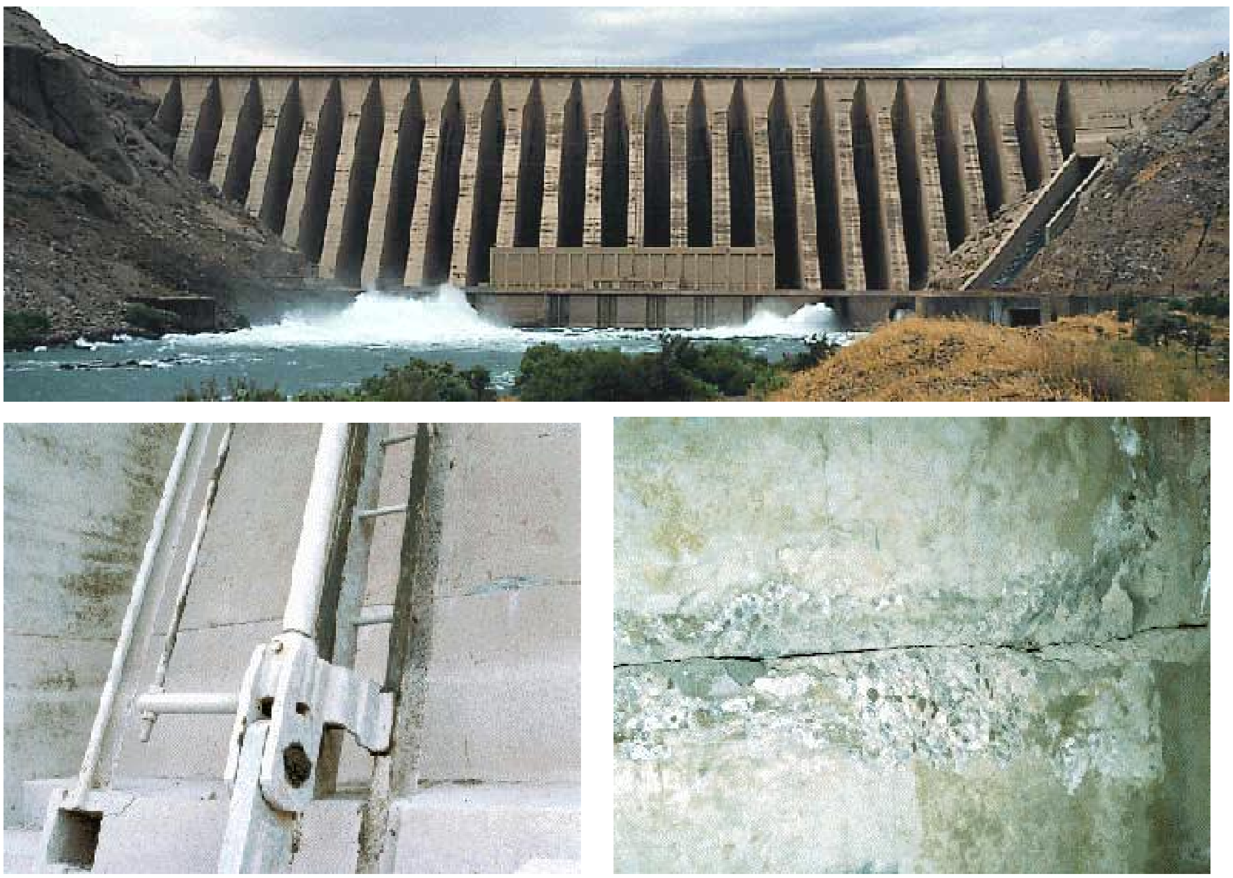

Fig. 2: Horizontal cracks at lift joints on upstream face of Sefid Rud buttress dam caused by the June 21, 1990 Manjil earthquake in the Northwest of Iran (M_s = 7.7, epicentral distance approx. 1 km). Top picture: dam shortly after the earthquake with open bottom and irrigation outlets for lowering of the reservoir; bottom left picture: horizontal crack at lift joint above intake; bottom right picture: detail of crack at lift joint with local spalling of concrete

From the point of view of dynamic stability of concrete blocks separated by cracks and joints, horizontal cracking planes of RCC dams are less problematic as compared to inclined cracks, which may occur in well-constructed conventional concrete dams. Numerical simulations have also shown that the sliding movement along a crack with an upstream inclination of 15° is about one order of magnitude larger than that of a perfectly horizontal crack (Wieland and Malla, 2000, Fig. 3). The understanding of the post cracking behaviour of concrete dams is essential for the safety assessment of a dam subjected to the MCE as the MCE is sufficiently strong to cause cracks in most concrete dams. This statement may even apply to concrete dams located in countries of moderate to low seismicity.

Based on these purely qualitative considerations, it may be concluded, that RCC dams are well suited to resist strong ground shaking. The smaller compressive strength of RCC as compared to that of conventional mass concrete, is not a problem for the seismic safety of RCC dams as cracking is governed by the tensile stresses developed in the dam body and the low dynamic tensile strength along interfaces (lift joints) and contraction joints.

General guidelines for the seismic design of concrete and embankment dams including RCC and CFR dams are given in a recent ICOLD Bulletin (ICOLD, 2001).

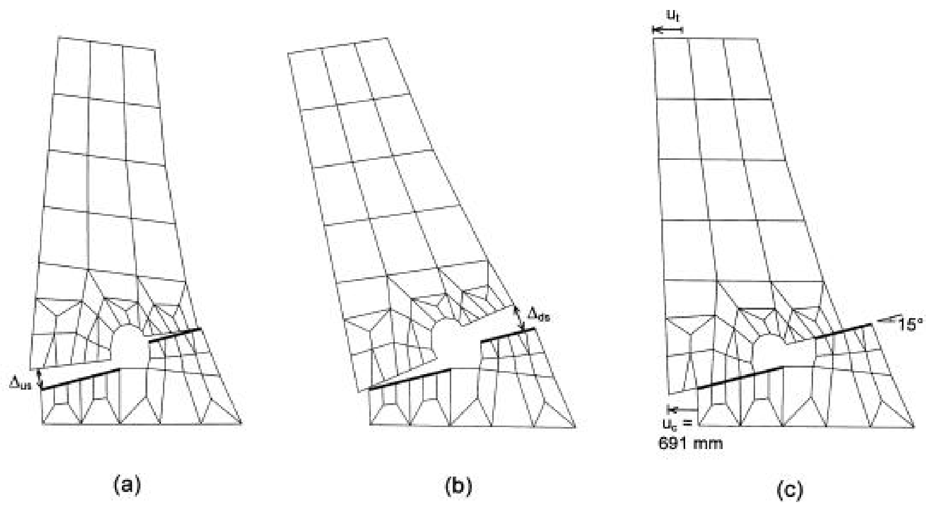

Fig. 3: Rocking and sliding motion of the upper portion of an arch-gravity dam detached by an inclined crack, (a) and (b), and final sliding movement after an earthquake with a peak ground acceleration of 0.5g, (c) (Malla and Wieland, 2003)

SEISMIC SAFETY ASPECTS OF CONCRETE-FACE ROCKFILL DAMS

According to Sherard and Cooke (1987) concrete face rockfill dams have no problems with safety during and after a strong earthquake. There is no pore pressure in the free-draining, heavily compacted rockfill and earthquakes will produce only small deformations. However, there is no case history of a modern CFR dam that was shaken by a very strong earthquake. The 85 m high Cogoti concrete face rockfill dam in Chile, 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 from the dam site of about 90 km produced a peak ground acceleration (PGA) of 0.19 g. 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 80 cm at the base to 20 cm at the top. The earthquake produced an instantaneous settlement of the crest of 40 cm.

A 17 m high, CFR saddle dam on the right abutment of Sugesawa dam in Japan was shaken by the October 6, 2000 Tottori earthquake (M_w=6.6). The PGA measured on the right abutment of the saddle dam was 0.36 g. No damage was observed (Matsumoto et al., 2001).

Both case histories are from regions of high seismicity and depending on the location of major CFR dams relative to geologic structures much higher ground motions can be expected at sites of high dams. More field experience exists with rockfill dams with internal sealing element and Seed et al. (1985) present results of two-dimensional analyses on the expected displacements on the downstream slope for different

PGAs. However, CFR dams 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 CFR dams 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, equivalent linear analysis, effective stress non-linear finite element or finite difference analysis (Bureau et al., 1985, 1997; Seed et al., 1985; Seco e Pinto, 1996). There is a general consensus that for well-designed and well-compacted dams, such as modern CFR dams, the use of simplified procedures or the equivalent linear analysis in combination with Newmark's sliding block analysis of slopes, produces a safe design.

The influence of the hydrodynamic water pressure on the face slab has been modelled in various ways either as an added mass or by introducing fluid-solid and fluid elements in the finite element model. The hydrostatic pressure increases the effective stress in the rockfill next to the slab and thus increases its stiffness. This effect is compensated by the hydrodynamic pressure so that the dynamic response is not changed significantly by the effect of the hydrostatic pressure.

Little attention has been paid to the behavior of the face slab although it is generally agreed that during a strong earthquake the face slab is likely to crack. But potential cracking and subsequent leakage do not impair the safety of the dam because the amount of leakage water that would pass through the structural cracks and the semi-pervious transition zone can easily be discharged by the free-draining rockfill downstream of the slab (Sherard and Cooke, 1987). There have been many cases in which large quantities of water have passed through compacted rockfill (from construction floods or major leakage through the face) with no significant effects, i.e. no settlement caused by through-flow. Sherard and Cooke (1987) explain this by the high contact stresses existing between the rockfill particles which produce friction forces that are much higher than the hydraulic drag forces. Only loose soil grains in the voids of the rockfill can be washed out by leakage water.

Since cracks in the slab are only an economic problem in that water is lost, there is little interest in sophisticated seismic analysis of the rockfill/slab system.

The effect of the topography of the valley has also a significant influence on the response of the embankment and the stresses produced in the concrete face. Gazetas (1987) remarked that narrow valleys with relatively rigid abutments create a stiffening effect whereby natural periods decrease and near-crest accelerations increase sharply as the canyon becomes narrower. Amplification peaks of the higher modes are also quite different, i.e. higher, than those predicted from two-dimensional dam models.

For the assessment of the seismic performance of the concrete slab of CFR dams 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. In the extreme case slab elements may be pushed upwards as shown in Fig. 4. Moreover, joints may open under tension.

Figure 4 shows the buckling (pushing up) of elements of a canal lining produced by the 1999 Chi-Chi earthquake in Taiwan and in Fig. 5 the sliding of concrete elements of a canal lining is depicted. These are figures, which may show some of the failure mechanisms that could occur in CFR dams.

Fig. 4: Buckling of canal lining elements caused by the September 21, 1999 Chi-Chi earthquake in Taiwan

With the face slab elements being much larger and heavier, a scenario of such a scale (Fig. 4) is not very likely but the mechanism can be the same. It is concluded that the analysis of the cross-canyon earthquake effect be considered in the seismic analysis of CFR dams 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 CFR dams.

Fig. 5: Irrigation canal lining damaged during the June 21, 1990 Manjil earthquake in Iran (rigid body movement of concrete elements)

The cross-canyon earthquake component can produce quite substantial stresses along the dam axis. This can be seen in Fig 6.

Fig. 6: Cracks at the crest of the 106 m high Sefid Rud buttress dam, caused by the June 21, 1990 Manjil earthquake in the Alborz mountain range in the Northwest of Iran. Left hand picture: local compression failure of deck slab at joint of two adjacent monoliths; central and right hand pictures: cracks on concrete slab on dam crest in direction of dam axis on different blocks (note: cracks shown are caused by the cross-canyon component of the ground shaking)

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 10 s duration and with a horizontal PGA of 0.18 g produced a joint opening of about 15 mm at the top of the slab (see Fig. 7). Joints repeatedly opened and closed during seismic loading and the slab movement followed that of the dam body.

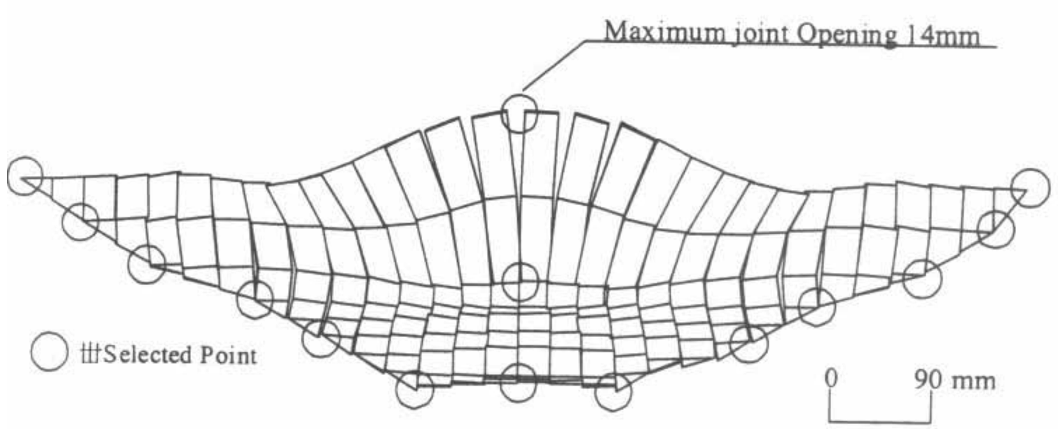

Fig. 7: Deformation of concrete slab obtained from dynamic analysis (Harita et al., 2000)

CONCLUSIONS

RCC and CFR dams are economically attractive alternatives to conventional dams. As no observations exist about the seismic safety of these dams, their seismic performance must be studied carefully taking into account all existing information.

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.

Well-designed and properly compacted CFR dams on rock foundations are considered safe under the strongest earthquake loading. This is because the crack width of the cracks in the face slab that may develop as a result of high dynamic stress and deformations, predicted from a traditional two-dimensional dynamic analysis of the highest dam section, are relatively small and thus the resulting leakage does not impair the safety of the dam. However, the behaviour of the concrete face during a strong earthquake is largely unknown especially when looking at the cross-canyon excitation, which up to now has been largely ignored because of its complexity. The large membrane forces in the 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. Besides, in narrow valleys the three-dimensional deformations of the dam due to an earthquake excitation in valley direction may lead to damage of joints (and compression and shear stresses in joints).

The largest CFR dams under construction have heights exceeding 200 m. Local damage of the concrete face (especially large joint displacements) due to earthquake action may drastically increase leakage losses. For the safety of very high CFR dams it is very important to know if the consequences of joint leakage (with large opening) under high hydrostatic pressure are similar to those under low to moderate pressures. As up to now no major CFR dam has experienced ground shaking similar to that expected during the maximum credible earthquake, the above scenarios are still of hypothetical nature.

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