EARTHQUAKE SAFETY OF AN ARCH-GRAVITY DAM WITH A HORIZONTAL CRACK IN THE UPPER PORTION OF THE DAM

Martin WIELAND[1] And Sujan MALLA[2]

SUMMARY

A horizontal crack first appeared along the downstream wall of the upper gallery of an arch-gravity dam after 25 years of operation. Since then, the crack has extended over the whole length of the upper gallery and the crack opening has been continually increasing. This has been accompanied by an irreversible displacement of the dam crest towards the upstream side. In addition, a second crack has appeared at the base of the upstream wall of the upper gallery. A detailed structural investigation has shown that the crack formation is most likely a result of ongoing alkali-aggregate reactions. A chemical analysis also indicates a relatively high potential for alkali-aggregate reactions in the dam concrete.

If the crack growth continues, a horizontal crack will eventually separate the upper portion of the dam from the lower portion. An investigation has shown that the dam is safe in this state under the static loads. For the assessment of the dynamic stability of the cracked dam under the earthquake loading, extensive numerical analyses have been performed using two different finite-element models:

(i) a two-dimensional model of the upper portion of the dam separated by an inclined crack, which is modelled using contact elements, and

(ii) a three-dimensional linear-elastic model of the uncracked dam-foundation system with incompressible reservoir.

Model (i) is used to perform the dynamic stability analysis of the cracked dam subjected to earthquake excitation. In this analysis, the radial acceleration at the level of the upper gallery of the dam, computed with model (ii), is used as the input motion.

The results of this study show that the dam with an inclined crack dipping at an angle of 15° towards the upstream side can withstand an earthquake load with a peak ground acceleration exceeding 0.5 g. The sliding displacement of the detached upper portion of the dam in the upstream direction due to this earthquake load is about 70 cm.

INTRODUCTION

A continuous crack was observed along the downstream wall of the upper gallery of the 45 m high arch-gravity dam shown in Fig. 1 after 25 years of operation. The crest length of the dam is 290 m, the crest width is 5 m and the maximum base width is 22 m. The total volume of the mass concrete is 71,000 m^3. The upper gallery is located about 15 m below the dam crest. The crack has already propagated along almost the whole dam length and the crack opening has been continually increasing at a rate of up to 0.1 mm per year. This has been accompanied by an irreversible displacement of the crest towards the reservoir by about 1.1 mm per year. A

[1] *Electrowatt Engineering Ltd., P.O. Box, Bellerivestrasse 36, CH-8034 Zurich, Switzerland*

[2] *Electrowatt Engineering Ltd., P.O. Box, Bellerivestrasse 36, CH-8034 Zurich, Switzerland*

similar crack has also been observed at the corner at the base of the upstream wall of the upper gallery. However, the crack opening of this crack is much smaller than that of the first crack.

For the investigation of this problem, a study was carried out using a three-dimensional finite-element model of the dam-foundation system. The thermal and elastic properties of the dam were determined with the help of the available records of the concrete and air temperatures, and the dam displacements measured by means of a pendulum located in the central part of the dam (Malla and Wieland, 1999).

The results of the stress analysis for a combination of gravity, temperature and water loads show that there are zones of relatively high tensile stresses on the walls of the upper gallery in summer at the locations of the observed cracks. However, these tensile stresses are not high enough to satisfactorily explain the formation of the cracks. Based on this study, the occurrence of alkali-aggregate reactions was identified as the most likely cause of the crack formation in the upper gallery of the dam. The testing of the mass concrete also shows a relatively high potential for alkali-aggregate reactions in the dam.

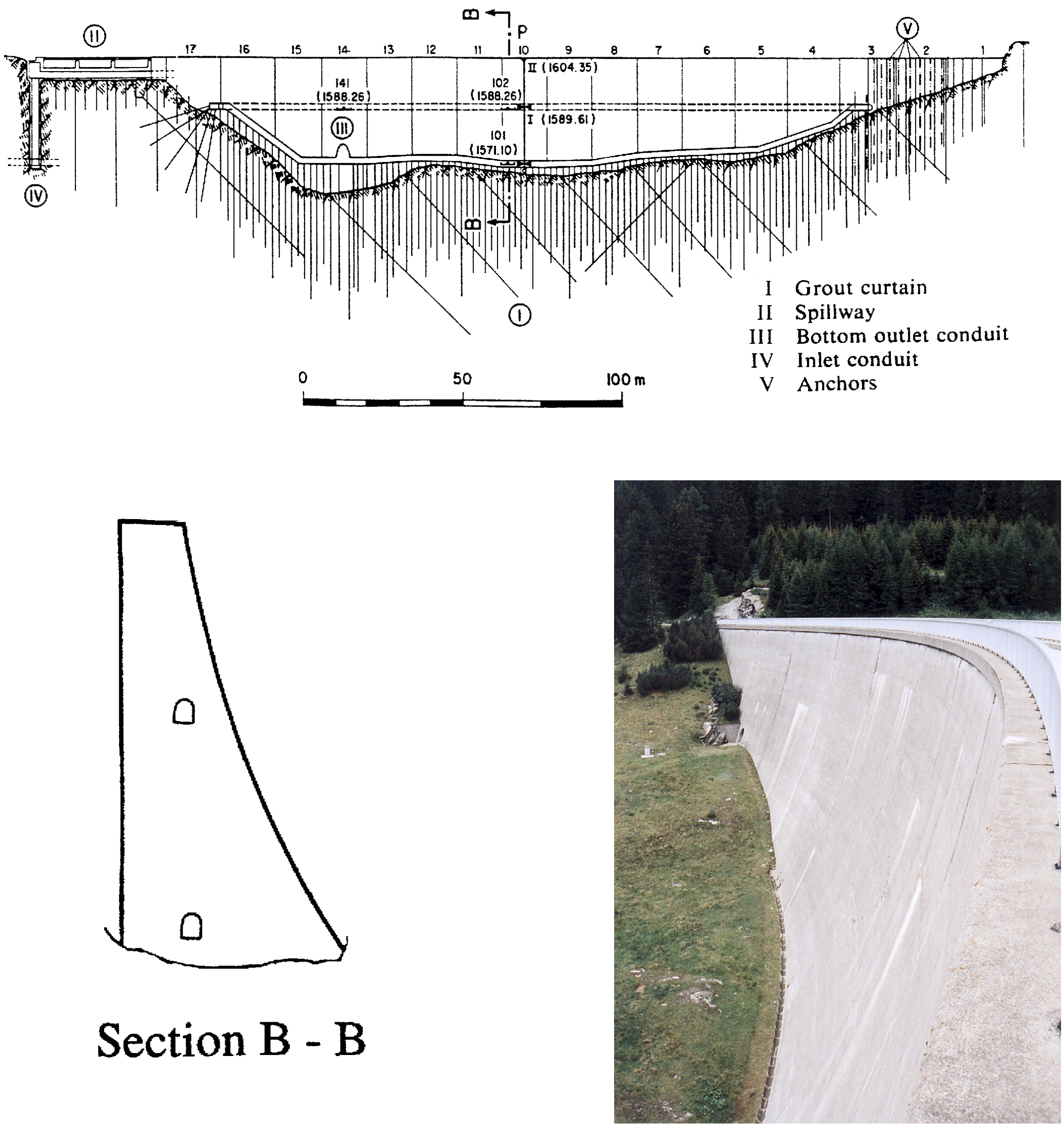


Fig. 1 Layout of arch-gravity dam, central cross-section and photograph showing downstream dam face

STATIC STABILITY ANALYSIS OF DETACHED UPPER PORTION OF DAM

Concrete cores were taken from the cracked part of the downstream wall of the upper gallery. The observation of the bore holes drilled to extract the cores shows that the crack is dipping at an angle of 15° towards the upstream side and that the depth of the crack exceeds 1.5 m. The thickness of the dam concrete on the downstream side of the upper gallery is about 2.8 m. The crack has, however, not yet been detected on the downstream face of the dam. Since the crack is of unstable nature, as shown by a fracture mechanics investigation (Malla and Wieland, 1999), it is expected to eventually propagate up to the downstream face of the dam

As there is a horizontal lift joint below the floor of the upper gallery, the crack at the base of the upstream wall of the upper gallery is likely to be horizontal. In the worst case, it could have the same inclination as the downstream crack.

Static stability analyses have shown that the sliding failure of the fully detached upper portion of the dam will not occur under the static loads even in the worst possible condition caused by a rapid drawdown. In this condition, the full uplift pressure (with a triangular distribution from the upstream dam face to the upper gallery) is still acting on the crack, whereas the water load on the upstream dam face (which has a stabilising effect) is no longer there.

STABILITY OF DETACHED UPPER PORTION OF DAM UNDER EARTHQUAKE LOADING

Pseudostatic Stability Analysis

The results of the conventional pseudostatic stability analysis of the detached upper portion of the dam subjected to earthquake loading are presented in Fig. 2.

The critical sliding acceleration is a function of the crack inclination and the coefficient of friction in the crack, which is in the range of 0.7 to 1.0. It has to be pointed out that only a movement of the detached concrete block towards the upstream side is possible due to the geometry of the arch-gravity dam. For a crack inclination of 15°, the critical pseudostatic sliding acceleration is 0.36 g.

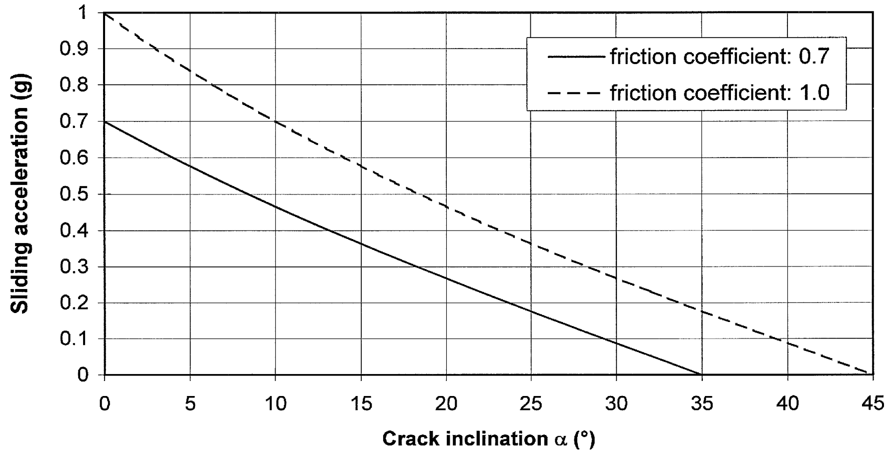
The critical pseudostatic acceleration which leads to the overturning of the upper portion of the dam is 0.32 g. This value is essentially independent of the crack inclination and the coefficient of friction. The results of the pseudostatic analysis would imply that the upper portion of the dam should overturn before it starts to slide for the case of a 15° crack. However, the results of the dynamic analysis, which are described in the following part, show that the earthquake shaking causes a sliding movement of the detached upper portion of the dam without producing an overturning instability.

Dynamic Analysis of Three-dimensional Dam-Foundation-Reservoir System

The three-dimensional finite-element (FE) model of the dam-foundation system shown in Fig. 3, with 41,634 dynamic degrees of freedom, was used to compute the time history of the acceleration in the radial direction at the level of the upper gallery in the highest block of the dam. In this analysis, the dam was assumed to be uncracked. Moreover, the foundation rock was assumed to be massless and the water in the reservoir to be incompressible.

For the evaluation of the earthquake safety of the dam, the full reservoir condition is relevant. For the full reservoir condition, the eigenfrequency of the lowest mode of the dam in the along-stream direction is 5.9 Hz, compared to 7.4 Hz for the empty reservoir condition. All the results presented in this paper were calculated for the full reservoir condition.

The time history of the radial acceleration at the base of the upper gallery for an earthquake with a peak ground acceleration (PGA) of 0.1 g is shown in Fig. 3 together with the corresponding floor response spectrum. The acceleration amplification factor with respect to the PGA is 3.8 at the upper gallery and about 8 at the dam crest.



- Overturning stability:
  Critical horizontal acceleration a_o

  $$a_o = \frac{s}{h}\, g$$

  $(s = 2.82 \text{ m},\ h = 8.92 \text{ m},\ a_o = 0.32 \text{ g})$
- Sliding stability:
  Critical horizontal acceleration a_s

  $$a_s = \frac{\mu \cos\alpha - \sin\alpha}{\cos\alpha + \mu \sin\alpha}\ g$$

  $(\mu = 0.7,\ \alpha = 15°,\ a_s = 0.36 \text{ g})$

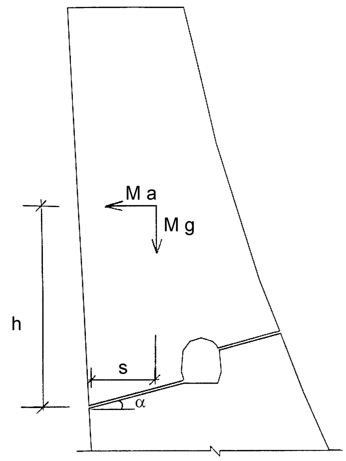


Fig. 2 Critical pseudostatic accelerations for sliding and overturning of detached upper portion of dam

Dynamic Stability Analysis

For the dynamic stability analysis, a two-dimensional finite-element model of the upper portion of the dam was used. The crack with an inclination of 15° was modelled with contact elements, which can transmit friction and compressive forces only. Coulomb friction was assumed in the crack. The mass concrete was assumed to be a homogeneous linear-elastic material. The dynamic analyses were carried out with the general-purpose computer program ADINA (ADINA, 1996). In order to get reliable results, very small integration time steps of 0.0001 s had to be used.

The time history of the radial acceleration at the level of the upper gallery (Fig. 3), which was obtained earlier from a full three-dimensional dam analysis, was used as the excitation acting at the base of this model. As the problem is nonlinear, a series of analyses were performed using several different accelerograms. Instead of repeating the full three-dimensional analysis of the dam-reservoir-foundation system, the floor response spectrum shown in Fig. 3 was used for the artificial generation of additional spectrum-compatible accelerograms (Gasparini and Vanmarcke, 1976). The calculations were carried out for different levels of earthquake loading (PGA varying from 0.1 g to 0.5 g) and for different values of the coefficient of friction (ranging from 0.5 to 1.0).

Typical results of the dynamic stability analysis are plotted in Figs. 4 and 5 for the coefficient of friction of 0.7 and the base excitation shown in Fig. 3 scaled up for a PGA of 0.5 g. During the rocking motion caused by the earthquake load, the maximum crack opening displacements at the upstream and downstream faces of the dam amount to 19 mm and 27 mm, respectively. After the earthquake, the detached upper portion of the dam will have moved in the upstream direction by 69 cm. For comparison, at the end of an earthquake with a PGA of 0.2 g, the sliding displacement is 3 cm.

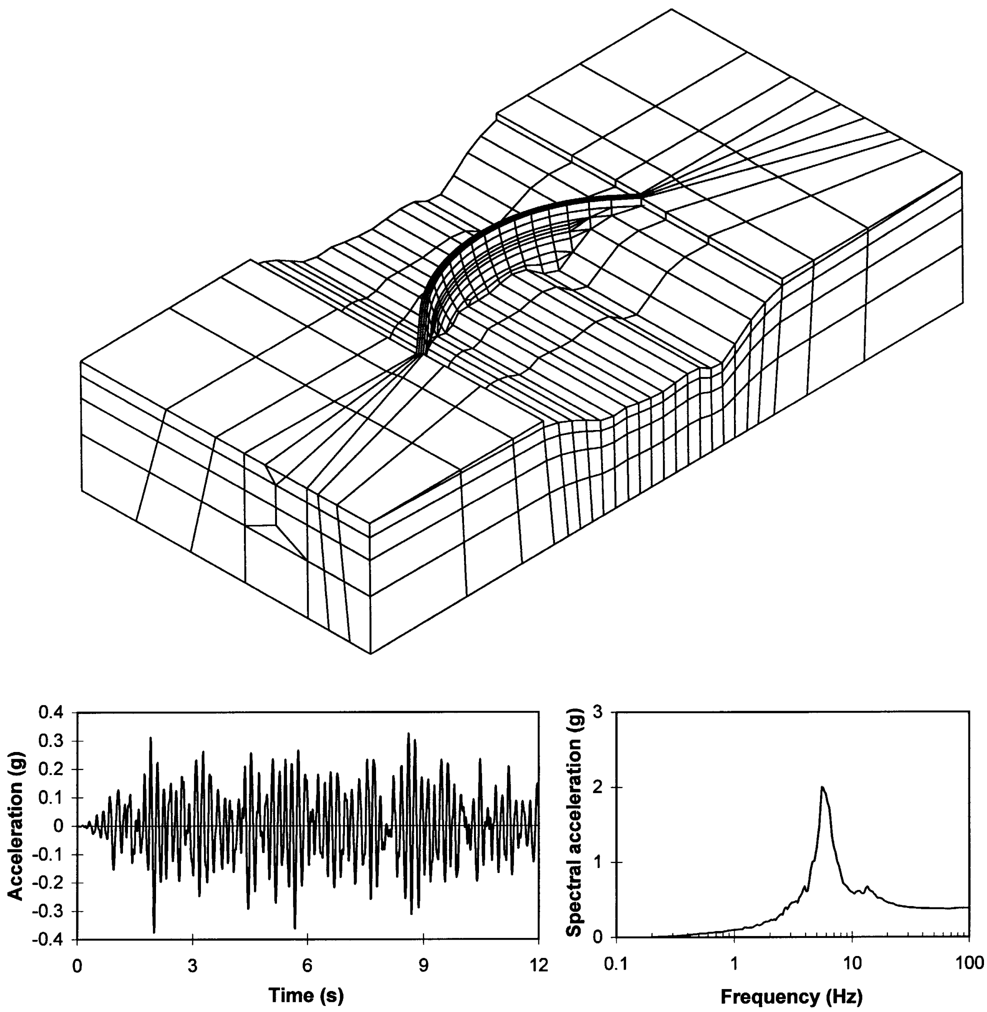


Fig. 3 Three-dimensional dam-foundation model (top) and time history of radial acceleration at base of upper gallery with corresponding floor response spectrum for PGA of 0.1 g (bottom)

The thickness of the dam is about 9 m at the level of the upper gallery. Therefore, a sliding displacement of 69 cm caused by an earthquake with a PGA of 0.5 g does not endanger the stability of the dam. Moreover, the PGA of the maximum credible earthquake at the dam site is well below 0.5 g. Therefore, the safety of the detached upper portion of the dam is ensured for the estimated crack inclination of about 15°. It is noted here that the stability of the dam would be substantially reduced if the crack inclination is significantly larger than 15°.

From Fig. 5, it is obvious that the final sliding displacement of the detached upper portion of the dam is proportional to the duration of the strong ground shaking. In the present study, the effect of water in the crack has not been considered. This could lead to a reduction in the frictional resistance in the crack. Moreover, it has been assumed that the mass concrete remains intact at the upstream and downstream rocking points, where very high local stresses are expected to lead to spalling of concrete. Spalling can also be the result of combined action of rocking and sliding motions. Such structural damage was, for example, observed at the Sefid Rud buttress dam, which was subjected to very intense ground shaking during the 1990 Manjil earthquake in Iran (Wieland et al., 1996; Wieland, 1999).

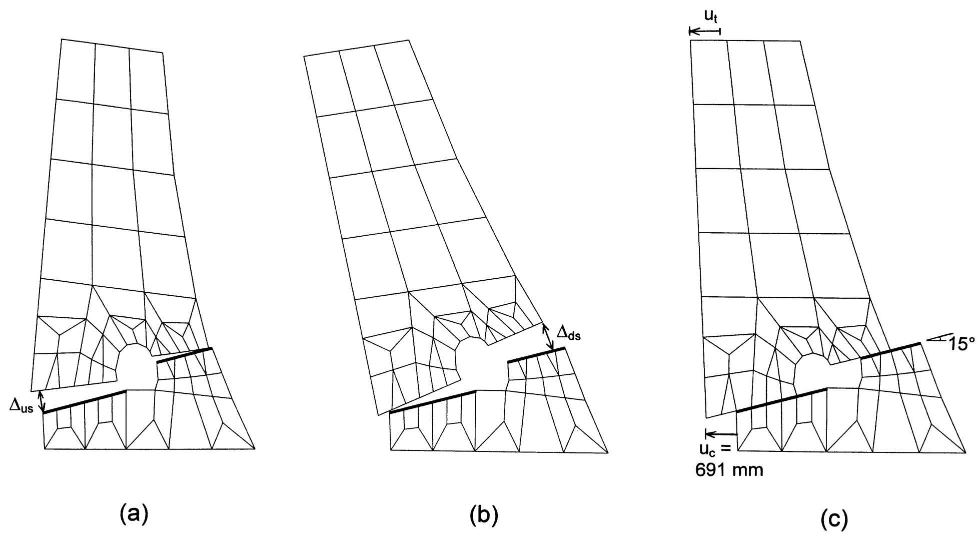


Fig. 4 (a) and (b) show the rocking of the detached upper portion of the dam during earthquake shaking, and (c) shows the final configuration with permanent sliding displacement after an earthquake with a peak ground acceleration of 0.5 g (coefficient of friction in crack: 0.7)

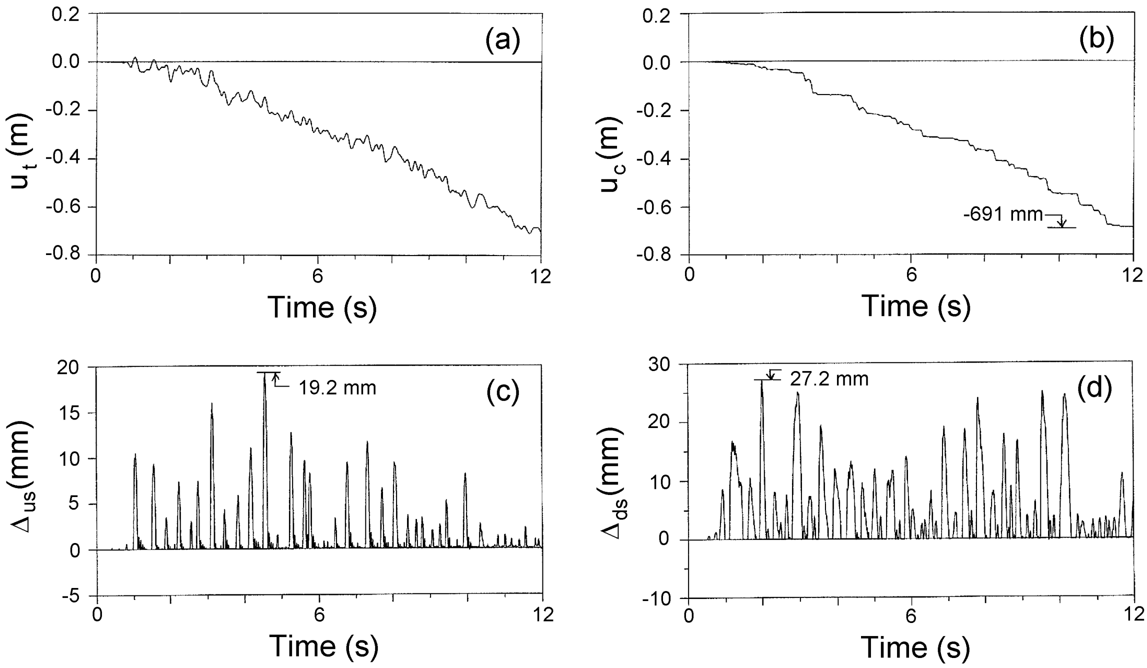


Fig. 5 Time histories of (a) radial displacement of dam crest, (b) sliding movement towards upstream along crack surface, (c) crack opening at upstream dam face and (d) crack opening at downstream dam face for earthquake excitation with peak ground acceleration of 0.5 g (coefficient of friction: 0.7; crack inclination: 15°)

Additional dynamic stability analyses have shown that the permanent sliding displacement of the upper portion of the dam are reduced to a few millimetres if the crack is horizontal. This is consistent with observations made at the Sefid Rud dam, where horizontal cracks developed mainly along lift elevations. In such a case, the dynamic response consists of mainly rocking motion.

CONCLUSIONS

The following conclusions can be drawn from the systematic investigations carried out for the assessment of the earthquake safety of the detached upper portion of the arch-gravity dam:

1. The maximum radial acceleration at the dam crest is about 8 times as large as the peak ground acceleration. The acceleration amplification factor at the level of the upper gallery is about 3.8.
2. During an earthquake, the detached upper portion of the dam with a 15° crack inclination can move by 3 cm and 69 cm in the upstream direction for peak ground accelerations of 0.2 g and 0.5 g, respectively.
3. Repeated rocking and sliding motions will lead to spalling of concrete at the upstream and downstream faces of the dam at the location of the crack.
4. The upper gallery represents a weak point in the dam where stress concentrations occur even without alkali-aggregate reactions.
5. The detached upper portion of the dam remains stable during an earthquake. However, water could penetrate into the upper gallery through the crack.
6. In a pseudostatic stability analysis, the upper portion of the dam would fail by overturning when subjected to a horizontal acceleration of 0.32 g. The failure mode for a pseudostatic earthquake loading is illustrated in Fig. 6. A dynamic stability analysis, however, proves that such a failure mode does not occur, as the failure will be due to sliding. The detached upper portion can, in fact, withstand a much larger ground acceleration without overturning than what one would expect on the basis of a pseudostatic analysis. The failure mode from a dynamic analysis of the detached upper portion of the dam under the earthquake loading is shown in Fig. 7.

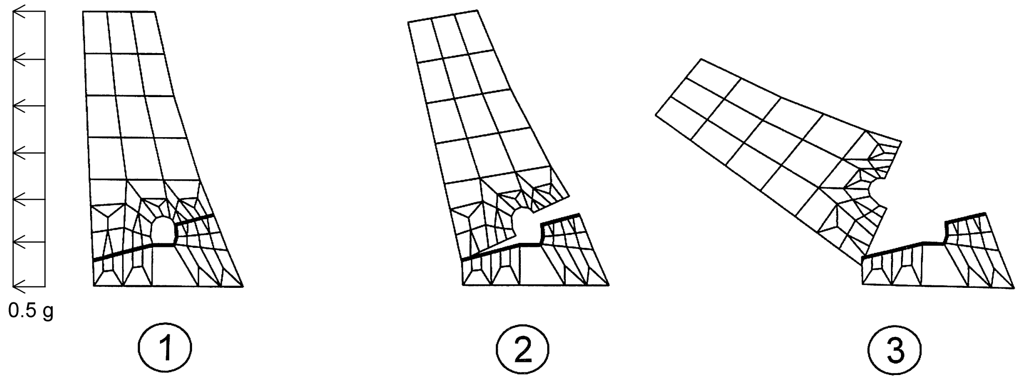


Fig. 6 Failure mode of the dam obtained from pseudostatic analysis (rocking failure)

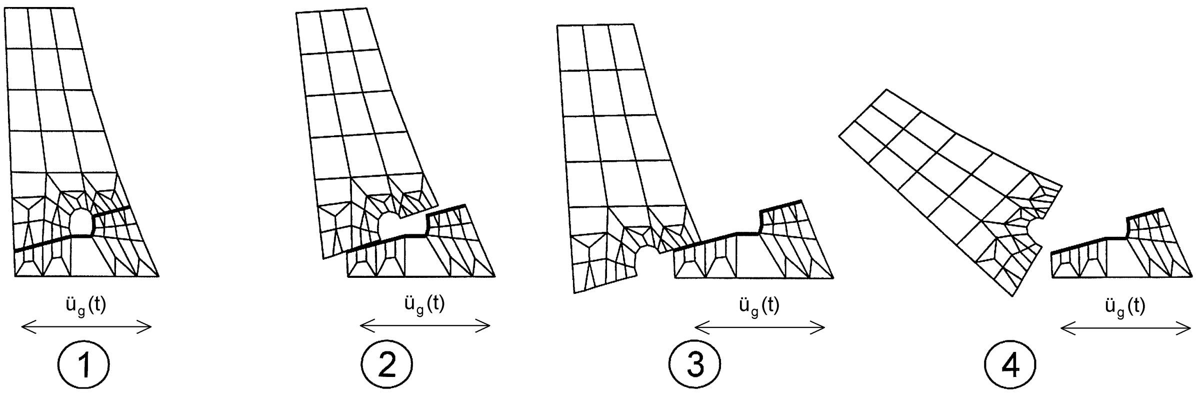


Fig. 7 Failure mode of the dam obtained from dynamic analysis for earthquake excitation with peak ground acceleration of 2 g (sliding failure)

REFERENCES

ADINA R & D (1996), ADINA User Interface Command Reference Manuals, Vol. I: ADINA Model Definition, Report ARD 96-2, ADINA R & D, Inc., Watertown, Massachusetts, USA.

Gasparini D. A. and Vanmarcke E. H. (1976), SIMQKE: A Program for Artificial Motion Generation, Department of Civil Engineering, MIT, Cambridge, USA

Malla S. and Wieland M. (1999), Analysis of an arch-gravity dam with a horizontal crack, Computers and Structures, Vol. 72, pp. 267-278

Wieland M. (1999), Seismic performance and assessment criteria for concrete dams, Dam Engineering, Vol. X, Issue 1, pp. 41-54

Wieland M., Brenner R.P. and Malla S. (1996), Aseismic design of arch and arch-gravity dams in zones of high seismicity and experience with earthquake behaviour of large concrete dams, Proc. Int. Symposium on Seismic and Environmental Aspects of Design of Earth, Concrete and Tailing Dams, Annual ICOLD Meeting, Santiago, Chile