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Nonlinear seismic response of concrete gravity dams due to foundation fault movement

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Abstract. Not only should dams be evaluated for seismic shaking, but their capability to survive potential fault displacement in their foundations should also be assessed. Safety reviews of existing dams suggest that geological-seismic evaluation of some dam sites has failed to recognize the existence of possibly active faults. In this study, the nonlinear seismic behavior of concrete gravity dams, due to relative fault dislocation occurring in foundations, has been investigated. Two types of fault movement, including normal-slip and reverse-slip, have been considered. These two types, combined with the location of fault lines, with respect to the toe, middle, and heel of the dam base, angle of fault, and water elevation in reservoirs, which result in 36 types of model, have been considered. Results show that each type of fault can cause propagation of specific crack patterns, and the angle and location of the fault beneath the dam have a great effect on the amount of damage induced. The water pressure of the reservoir can also have increasing or even decreasing effects on the crack propagation rate. The existence of foundation fault movement beneath concrete gravity dams, depending on the condition of the problem, can cause rapid crack propagation in the dam body, jeopardize stability, and significantly change the dam's dynamic response.

1. Introduction

Generally, concrete dams have not been sited at locations where faults are classified as active. However, there may be sites suitable for concrete dams where there is some possibility of fault displacement occurring underneath the dam. In addition, there may be situations where an existing dam was constructed over a fault thought to be inactive and later determined to be active, due to different approaches of classification. Also, some discontinuities may be observed during construction. In these cases, nonlinear analyses and criteria will be required to assess the capability of the concrete dams to safely withstand fault displacement [1-5].

There is a method with simplified assumptions to investigate concrete stresses due to fault displacement in concrete gravity dams, the foundation model of which consists of a fixed and movable block separated by elastic orthotropic elements [6]. However, this method does not represent a real fault movement in the foundation and introduces spurious forces or moments to the system. Also, some case studies to assess dam stability under foundation fault movement have been carried out [7-14].

In this study, a comprehensive investigation to assess the nonlinear seismic behavior of concrete gravity dams under the effect of foundation fault displacement,

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depending on the different type, angle, and location of faults underneath the dam, have been carried out using finite element simulation [15,16].

2. Techniques of introducing fault into finite element

Several schemes for treating faults and cracks in bedrock have been proposed in the past [17-21]. A four node element of zero thickness is introduced parallel to the fault plane [22]. To model a slip event, shear stiffness is assumed to be a very low value in the direction of slippage. In another approach, the fault plane is defined by a series of pairs of adjacent nodes [23]. In the split node technique, displacement at nodes which are shared by different elements is normally the same for each element [24,25]. The mentioned methods are not well adapted to the description of a fault slip. Some of them result in inaccurate or unstable solutions, and avoid the manifestly incorrect procedure of specifying the absolute displacement of nodes at the fault plane (which would rigidly fix the fault plane in space, prohibiting the normal elastic response of the grid and generating spurious stresses).

The technique which is of interest to us has been proposed by Melosh et al. They demonstrated that a modification of Jungels' split node technique can be implemented on a local level. The modification induced by this splitting can be contained in the load vector, so that the stiffness matrix is not altered. They showed that no net forces or moments are applied to the grid when isoparametric elements are used [26]. In this technique, a single node, when referred to an element on one side of a fault, can have a displacement, u^+, while it has a different displacement, u^-, when referred to an element on the other side of the fault. The fault is thus defined by a single line of such split nodes. The finite element grid is the same whether the nodes are split or not. The foundation of the dam is considered as the domain, Ω, with boundary Γ and fault line Π, in which the eth element domain is denoted as Ω^e and its boundary is denoted as Γ^e (see Figure 1).

All modifications that should be undertaken to exert fault movement into the foundation are about adding the following statement to the consistent local load vector of the split nodes:

$$\Delta F_p^e = -\sum_{q=1}^{M_d} X_{pq}^e \Delta U_q^e, \tag{1}$$

In the above equation, p and q are element (local) equation numbers, M_d is the number of element nodes times the number of components of the displacement defined at each n node, K^e is the local stiffness matrix of the element, and ΔU_q^e is relative fault displacement,

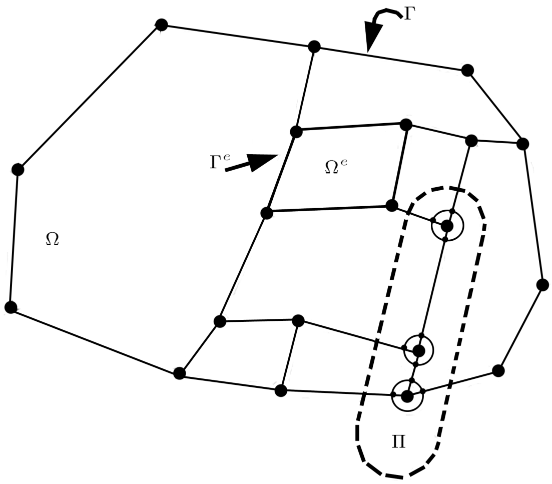


Figure 1. A general region of a continuum Ω with boundary Γ is subdivided into nonoverlapping elements Ω^e with boundaries Γ^e. Nodes (black dots) defines the intersection of elements. The subset Π (circled dots) are split nodes representing a fault or rock [26].

which are the same in magnitude but have different signs for each side of the fault.

3. Method

If the axis of a dam and fault line, both, lie in the same direction, two dimensional modeling of the dam-foundation-reservoir can be adopted. To consider the fault effect in the foundation beneath the dam, incremental nonlinear static analyses under loads induced by fault relative movement are carried out. Then, having cracks propagated and stresses induced on the dam monolith, nonlinear seismic analyses are assessed and the dynamic behavior of the dam is compared with conditions under which there is no fault movement in the foundation.

Two types of fault movement in two dimensional problems, including normal-slip and reverse-slip, have been considered. In order to investigate the concrete stresses under different angles of fault dislocation, faults with 45°, 68° and 90° were located in the foundation. Also, to see the effect of fault location, with respect to the dam base, the intersection of the fault line and the dam base should be at the heel, the middle and the toe. The effect of the water pressure of a reservoir was assessed by analyzing models under both full and empty reservoir conditions. Combining the above conditions resulted in 36 types of diverse model, which can mainly represent the effects of a foundation fault movement underneath the dam.

3.1. Finite element model

All models have been simulated by a 2D finite element computation method. For nonlinear analysis of the models, the NSAG-DRI (Nonlinear Seismic Analysis

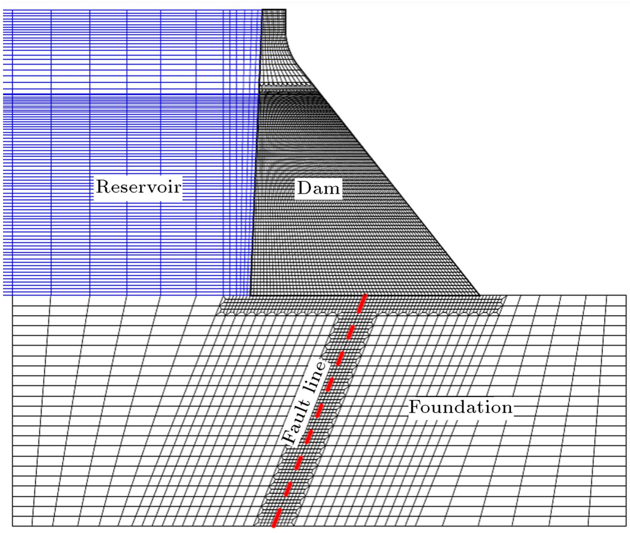


Figure 2. A finite element model of a dam-foundation-reservoir system with foundation fault (dashed line).

Table 1. Properties of dam concrete.

Elastic modulus	27580 MPa
Poisson's ratio	0.2
Unit weight	24357 N/m^3
Static fracture energy	300 N/m
Static tensile strength	2.4 MPa
Dynamic magnification factor	1.2

Table 2. Properties of foundation rock.

Elastic modulus	22400 MPa
Poisson's ratio	0.33
Unit weight	25928 N/m^3

of Gravity dams including Dam-Reservoir Interaction) program, in plane stress mode, has been used.

Figure 2 demonstrates the finite element mesh of the dam-foundation-reservoir of a model with a normal-slip fault, with a 68° inclination, located at the middle of the dam base and a full reservoir. Properties of the dam concrete and the foundation rock are shown in Tables 1 and 2.

4. Result of analysis and discussion

Incremental static nonlinear analyses of the Pine Flat dam were carried out for all models. The crack pattern of the sample condition of 68°, a normal-slip fault, located at the middle part of the dam base with a full reservoir, is demonstrated in Figure 3. In this set of figures, crack profiles induced by the foundation fault movement have been depicted for specific values of the relative displacement of the fault.

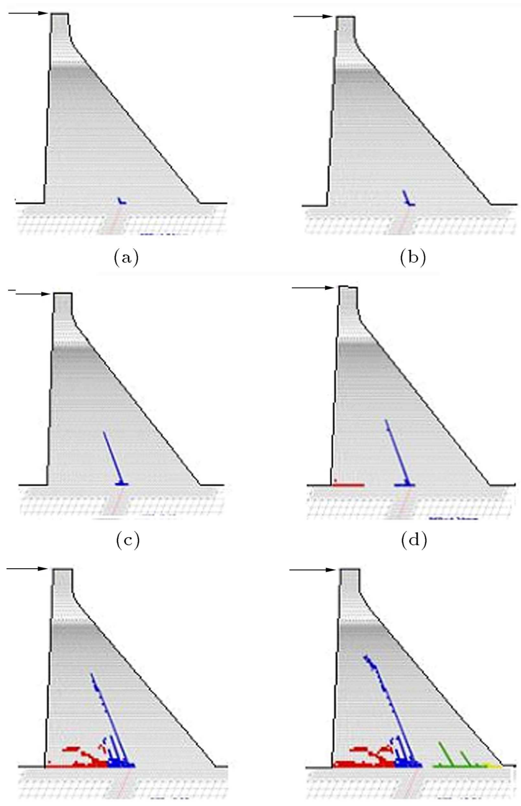
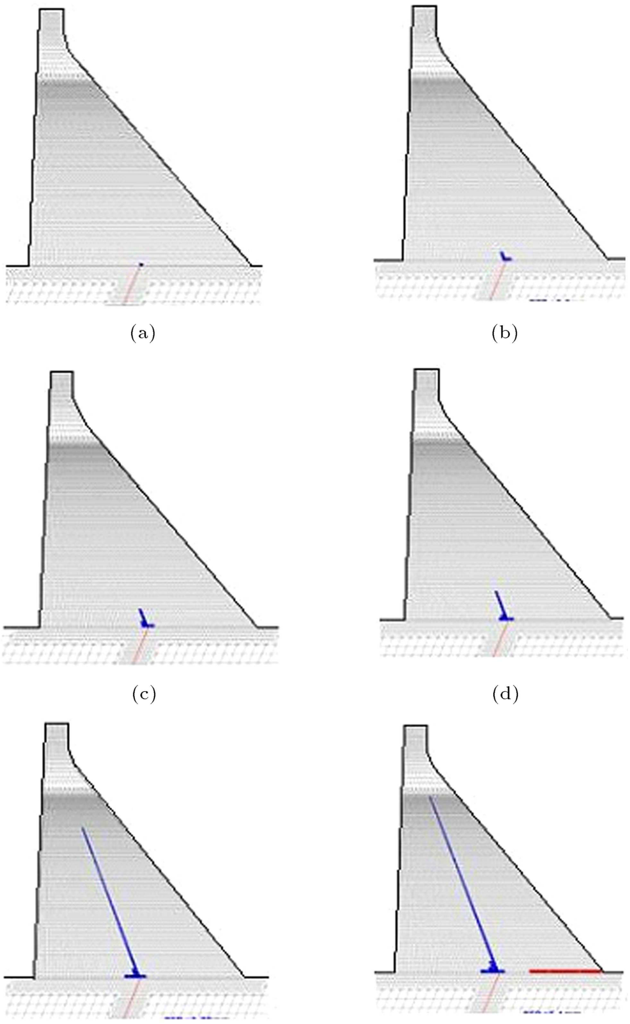


Figure 3. Crack pattern propagated in dam body due to normal-slip fault displacement with 68° inclination located at middle part of the dam base and full reservoir during incremental nonlinear static analysis of foundation fault movement: (a) 1.5 mm, (b) 1.80 mm, (c) 3.69 mm, (d) 4.34 mm, (e) 6.20 mm, and (f) 10.14 mm relative displacement of the fault.

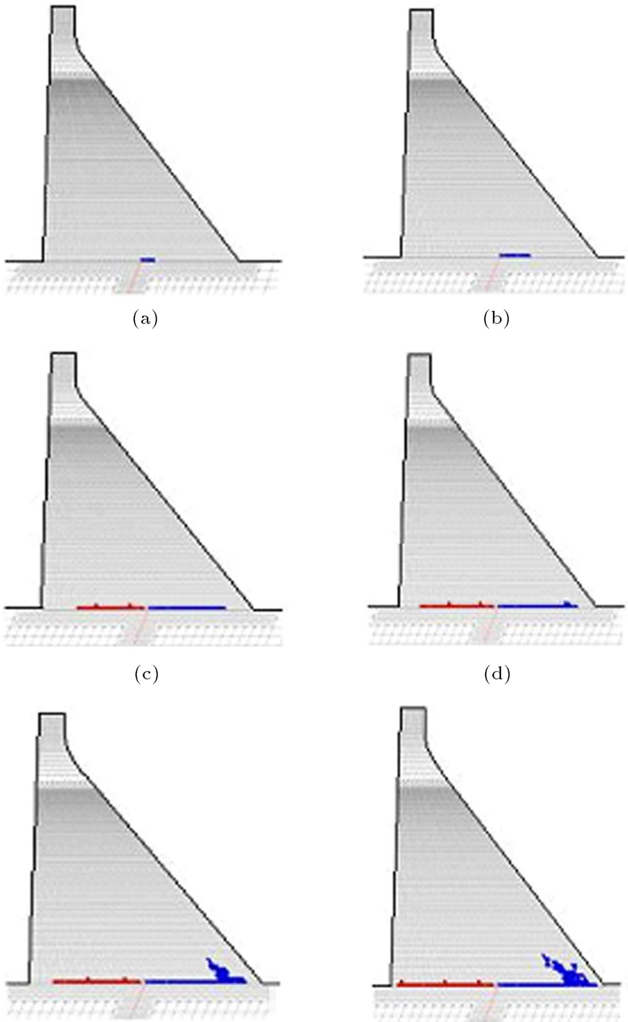
It can be seen that crack propagation initiates with a small value of fault dislocation. At the beginning of the fault movement, cracks propagate right at the intersection of the fault line and dam base and then dip in the dam body vertically and progressively. As the increment goes forward, a secondary crack profile at the upstream end of the base starts to propagate toward the downstream end, horizontally. When the faults relative displacement reaches a certain value, another crack propagation onset appears at the dam-foundation interface which spreads towards upstream, horizontally.

Figure 4 shows crack propagation in the monolith under the same conditions but with an empty reservoir. Compared to the full reservoir, the vertical crack propagation rate has been increased and, for this model, a secondary horizontal crack profile starts to appear at the downstream end of the dam-foundation intersection. By comparing empty and full reservoir analyses, it can be deduced that, for a certain length of vertical crack propagation, the dam with a full reservoir can experience more foundation fault movement.



(a) (b) (c) (d) (e) (f)

Figure 4. Crack pattern propagated in dam body due to normal-slip fault displacement with 68° inclination located at middle part of the dam base and empty reservoir during incremental nonlinear static analysis of foundation fault movement: (a) 1.10 mm, (b) 2.60 mm, (c) 2.75 mm, (d) 3.12 mm, (e) 3.79 mm, and (f) = 5.10 mm relative displacement of the fault.



(a) (b) (c) (d) (e) (f)

Figure 5. Crack pattern propagated in dam body due to reverse-slip fault displacement with 68° inclination located at middle part of the dam base and full reservoir during incremental nonlinear static analysis of foundation fault movement: (a) 0.70 mm, (b) 1.80 mm, (c) 2.80 mm, (d) 4.10 mm, (e) 5.50 mm, and (f) 7.00 mm relative displacement of the fault.

In Figures 5 and 6, models are the same as the above, respectively, for full and empty reservoirs, but the types of fault were changed to reverse-slip. When the reservoir is full (see Figure 5), as the nature of the fault movement changes, the crack pattern changes too, so that the damaged area is mainly in the dam-foundation intersection. In the beginning of incremental analysis, cracks start to propagate at the downstream, where the fault tends to move downward and induces tensile stresses on the dam concrete. Comparing this model to the model in which the reservoir is empty (Figure 6), it can be deduced that the water pressure mitigates the effect of fault movement at the upstream by producing tensile stresses at the upstream zone. Hence, in this model, water effects on the upstream face may postpone the onset of upstream crack propagation to some next incremental steps. Obviously, the effect of water is up to a certain level and its effect decreases as the fault relative displacement increases.

Comparative and categorized results of other models are described and demonstrated as follows.

4.1. Effect of fault type

Despite the angle or location of a fault beneath the dam, significant vertical crack propagation can be seen in the normal slip fault (Figure 7). For the same types of model but with a reverse-slip fault, cracks tend to appear at the lowest part of the monolith, and propagate right at the interface

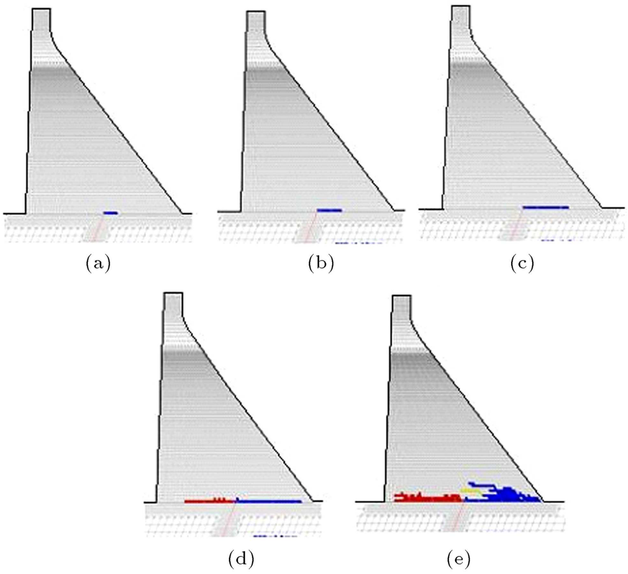


Figure 6. Crack pattern propagated in dam body due to reverse-slip fault displacement with 68° inclination located at middle part of the dam base and empty reservoir during incremental nonlinear static analysis of foundation fault movement: (a) 0.50 mm, (b) 1.10 mm, (c) 1.80 mm, (d) 2.50 mm, and (e) 4.85 mm relative displacement of the fault.

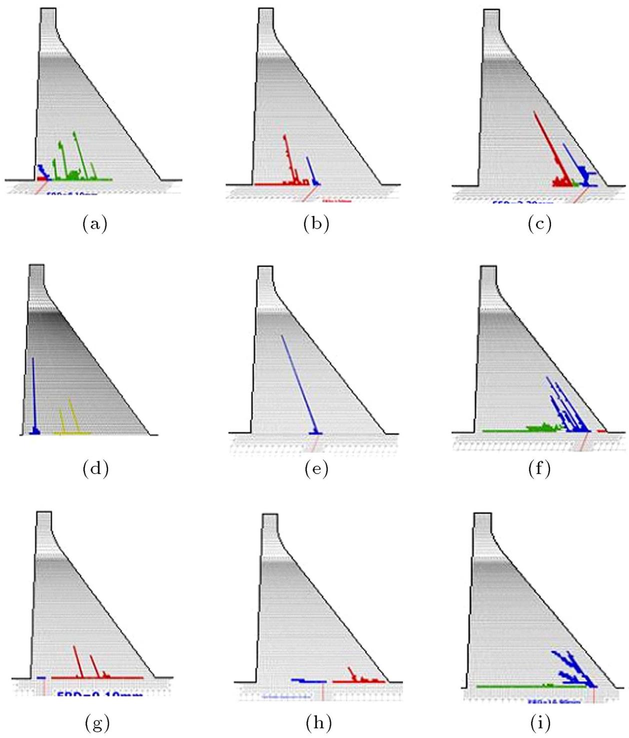


Figure 7. Crack propagation pattern in normal-slip fault: (a), (b), and (c): 45° fault with fault location in heel, middle and toe of the dam base, respectively; (d), (e), and (f): 68° fault with fault location in heel, middle and toe of the dam base, respectively. (g), (h), and (i): 90° fault with fault location in heel, middle and toe of the dam base, respectively.

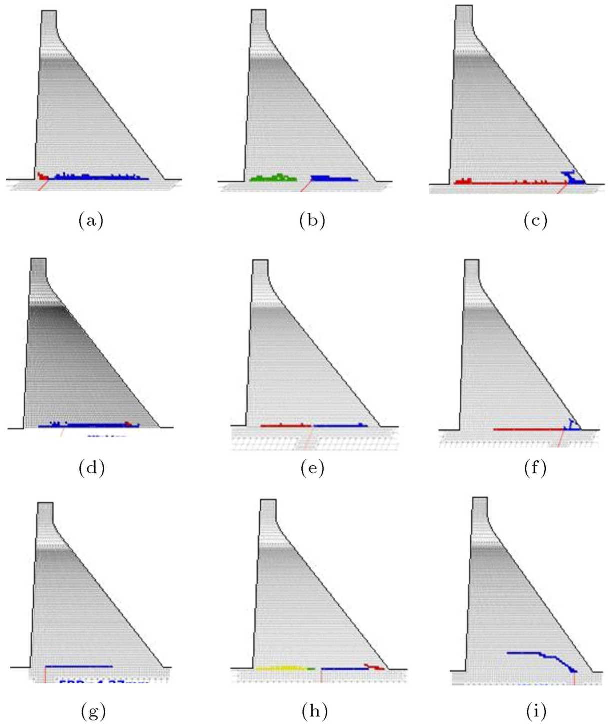


Figure 8. Crack propagation pattern in reverse-slip fault: (a), (b), and (c): 45° fault with fault location in heel, middle and toe of the dam base, respectively; (d), (e), and (f): 68° fault with fault location in heel, middle and toe of the dam base, respectively; (g), (h), and (i): 90° fault with fault location in heel, middle and toe of the dam base, respectively.

between the dam and the foundation, horizontally (Figure 8).

It can be inferred that, in normal-slip fault, the foundation tends to diverge along a horizontal direction, so, it rips the dam body upward, corresponding to the fault movement. Where the type of the fault movement changes to reverse-slip, the foundation tends to converge along a horizontal direction, so the dam body experiences contracting forces. For this reason, a kind of separation occurs at the dam-foundation interface; the dam is heaved up, and horizontal crack profiles would be resulted at the dam-foundation interface.

4.2. Effect of hydrostatic pressure

4.2.1. Normal-slip fault

When the reservoir is full, vertical crack propagation is faster. In the case of an empty reservoir, although the onset of crack propagation (in which the dam body is under tensile stresses at the upstream end of the dam foundation interface due to water pressure) is faster, vertical crack propagation is slower than in a full reservoir. Water pressure causes other forces to be exerted on the other axis and leads to decreased vertical but hastened horizontal crack propagation at the dam-foundation interface. As the fault relative

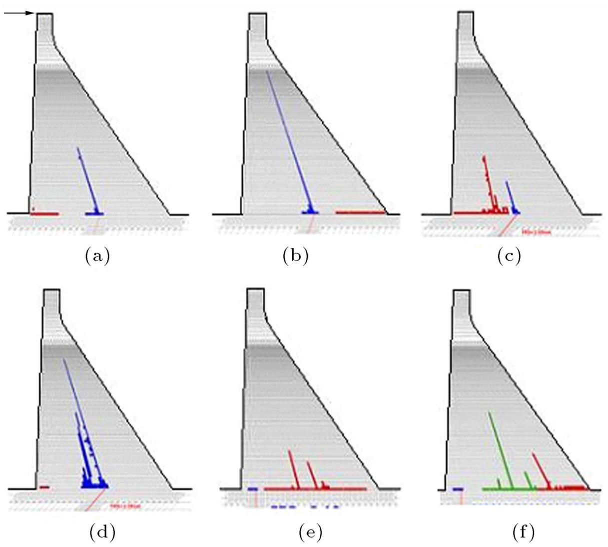


Figure 9. Effect of reservoir pressure on crack propagation for normal-slip fault type: (a), (c), and (e) are full reservoir; (b), (d), and (f) are empty reservoir. For each pair of full and empty reservoir foundation, fault relative displacements are identical.

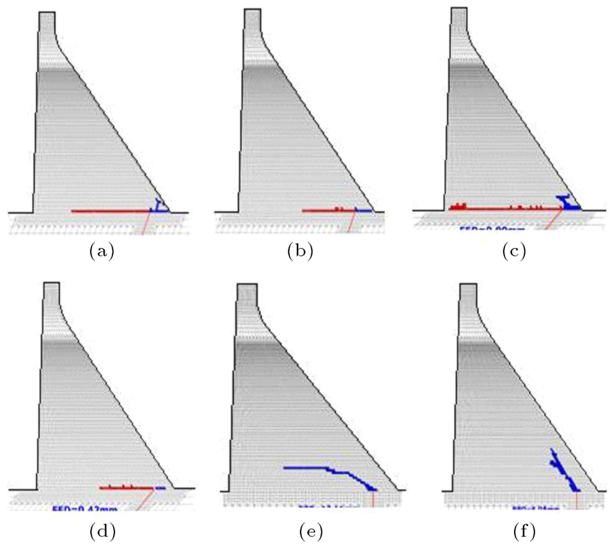


Figure 10. Effect of reservoir pressure on crack propagation for reverse-slip fault type: (a), (c), and (e) are full reservoir; (b), (d), and (f) are empty reservoir; for each pair of full and empty reservoir foundation fault relative displacements are identical.

displacement increases, the effect of water pressure dwindles (Figure 9).

4.2.2. Reverse-slip fault

At 68° and with reverse-slip fault, when the reservoir is empty, at the right side of the fault, where the hanging wall of the fault moves downwards and leads to the induction of tensile stresses on the dam monolith, cracks initiate to propagate faster. Under the same conditions but in a full reservoir, the hydrostatic pressure of the reservoir mitigates some effects of the faults by inducing compressive forces, so that the onset of cracks appears at higher incremental steps of the fault movement at the toe (Figure 10). Therefore, the effect of water causes the cracks to propagate at the interface between the dam and the foundation at the toe.

Generally, if the monolith is assumed to be a cantilever beam, considering the location of its neutral axis, location, and type of fault, the resultant consequences of both water pressure and fault dislocation can have increasing or decreasing effects on crack propagation throughout the dam. An interesting result can be obtained from the condition of a 90° fault, where the foundation moves only vertically and the fault is located at the toe. In this case, when the reservoir is empty, cracks tend to rip the dam body and go towards the crest. When the reservoir is empty, although the onset of crack propagation is faster due to shear stresses induced by water pressure on the mentioned cantilever beam, vertical cracks are inclined to change the direction of their growth and continue to propagate horizontally and faster towards upstream (Figure 10(e)).

4.3. Effect of foundation fault location

Fault location with factors such as type of fault and the uniform distributed weight of the dam on the foundation can, all together, affect the pattern, origin, starting point and mode of crack propagation (Figures 7 and 8). According to the supposed cantilever beam, the location of its neutral axis and the fault in the foundation, the portion of body weight on each side of the fault, and the upward or downward vertical dislocation of the fault sides, the crack pattern may be altered. In general, that side of the fault which carries a lower portion of the body weight of the dam is more vulnerable to damage. Comparing the results of models with the fault in the toe and models with the fault in the middle or heel of the dam, it can be inferred that, for the same value of relative displacement, the fault in the toe can be more harmful and causes more damage to be spread through the dam.

4.4. Effect of fault angle

A sharper angle can cause more damage to the dam (see Figure 11). Despite the location of the fault, the full or empty reservoir, and the type of the fault, it can be described that, for the same value of fault relative displacement, the sharper (less) angle of fault has a more horizontal component of displacement. In other words, the foundation experiences more convergent or divergent movement when the fault dislocates. Therefore, the sharper the angle of the fault is, the more is the effect on the dam. Obviously, the value of the fault angle can affect the direction of the vertical crack propagation in the dam, depending on reservoir conditions and meshing pattern.

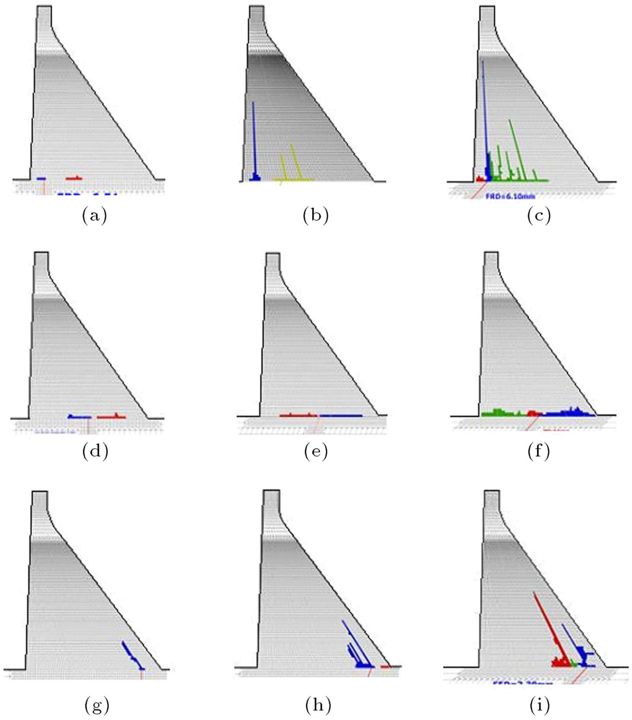


Figure 11. Effect of fault angle on induced damage on the dam body: (a), (d), and (g): 90° fault locating at heel, middle and toe of the dam base, respectively; (b), (e), and (h): 68° fault locating at heel, middle and toe of the dam base, respectively; (c), (f), and (i): 45° fault locating at heel, middle and toe of the dam base, respectively. For each row of figures fault types and relative displacements are identical.

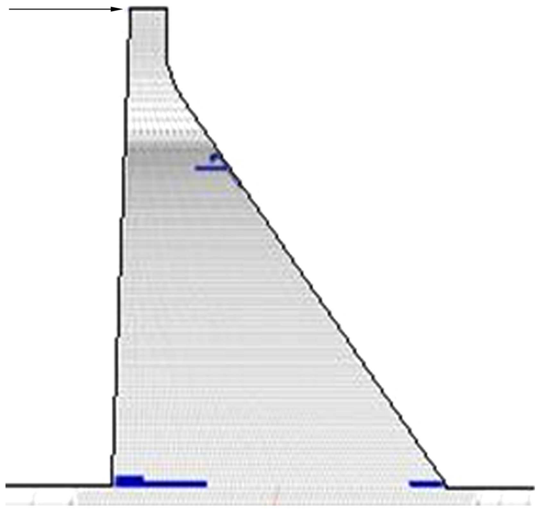


Figure 12. Crack profiles in the dam body under seismic loading and no fault dislocation at $T = 4.9$ sec.

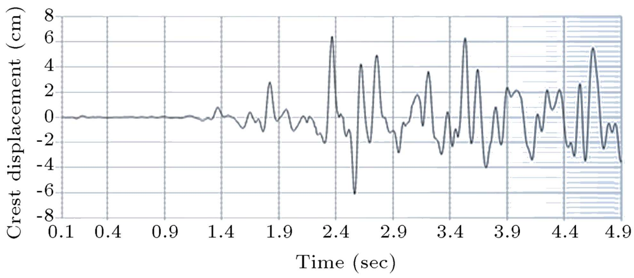


Figure 13. Crest displacement of the dam under seismic loading and no fault dislocation.

4.5. Connectivity in the interface between dam and foundation

In all the above analyses, there is a complete connectivity between the dam and the foundation elements in the finite element models, but material properties are different for dam concrete and bed rock. As the starting point of the cracks for small dislocations of fault occurred at this interface rapidly, this connectivity was loosened by defining a row of partially cracked elements at the mentioned interface, and the analyses were renewed. For the same value of foundation, fault movement, slight changes in crack pattern and damage to the dam were observed during the second analyses. The superabundant weight of the dam does not allow any significant slippage between the dam and the foundation or overturning the dam body; hence, the dam tends to crack.

4.6. Dynamic analysis of pine flat dam

Dynamic analyses of the dam were carried out both before and after the foundation fault movement. So, the effects of cracks and damage induced by foundation fault movement on the dynamic response of the dam can be investigated. A model of a 68° normal-slip fault, located in the middle part of the dam, with a full reservoir, is discussed here. The foundation was massless and boundary conditions were changed as the dynamic analysis was carried out. Figure 12 shows crack profiles under dynamic analysis of the above model with no fault movement at $T = 4.9$ sec under an earthquake produced by the same type of fault (normal-slip), and records are a projection of the fault plane with a PGA of 0.45 g. Figure 13 shows crest displacement during the analysis.

Figure 14 demonstrates crack patterns under only foundation fault movement, until relative fault movement reaches 3.50 mm. After propagating cracks through the dam due to foundation fault movement, dynamic analysis under the same earthquake records was carried out. Figure 15 depicts crack profiles propagated through the dam under both foundation fault movement and earthquake loading. Comparative crest displacements under both conditions of dynamic analyses were depicted in Figure 16.

According to the above figures, it can obviously be seen that considering foundation fault movement in the analysis not only changes the crack pattern in the dam body, but also changes the dynamic response of the concrete gravity dam.

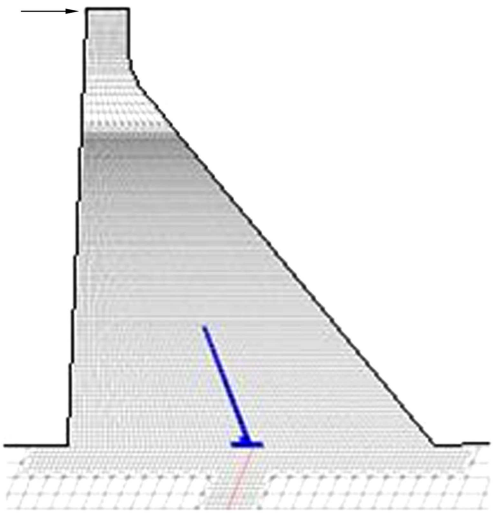


Figure 14. Crack pattern propagated through the dam body under 3.5 mm foundation fault movement.

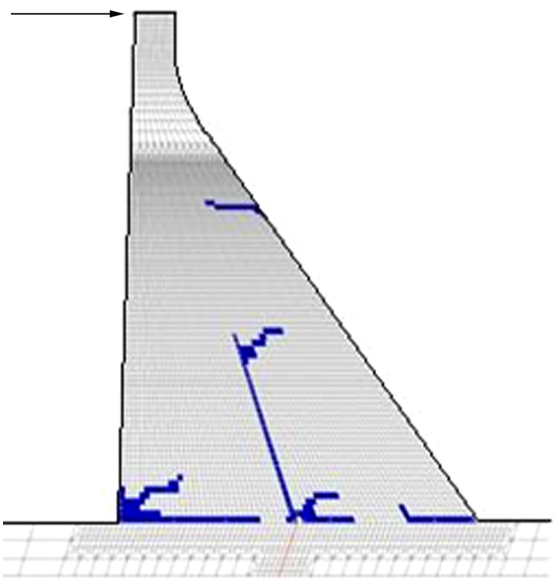


Figure 15. Crack pattern propagated through the dam body under both 3.5 mm foundation fault movement and seismic loading.

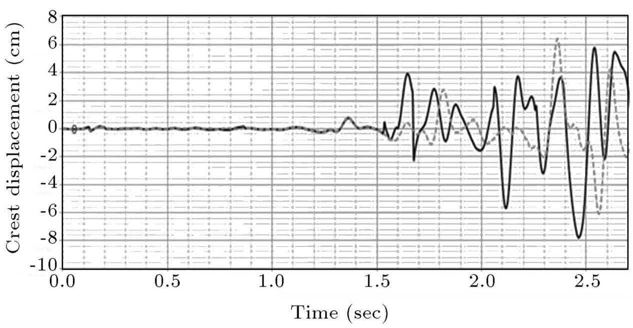


Figure 16. Crest displacement of the dam. Solid line: under both foundation fault movement and seismic loading; dashed line: under seismic loading and no foundation fault movement.

5. Conclusion

In this study, diverse models of foundation fault movement beneath a concrete gravity dam have been analyzed, and, according to the figures provided, the following conclusions may be drawn:

- Foundation fault movement, even a small dislocation, can cause a significant crack profile to propagate through the dam and seriously jeopardize its stability.
- Relative displacement in the foundation due to normal-slip fault, depending on its magnitude, leads the dam monolith to be ripped to shreds, and, crack patterns are mainly vertical towards the crest. For the same model, but with reverse-slip fault movement, cracks are horizontal at the interface between the dam and the foundation, and fault movement tends to lift up the dam.
- Water pressure at the upstream face may affect the pattern of crack propagation and has an increasing or decreasing effect on the magnitude of damage, depending on the type, angle, location and magnitude of the relative displacement of the fault.
- The closer the fault line to the upstream or downstream side of the dam is, the more damage there is on the dam body. Locating a fault line near the toe is the most vulnerable situation for certain dislocation of a fault movement.
- Sharper fault angles, with respect to the horizontal axis of the foundation, can do more serious damage to the dam body.
- The superabundant weight of the concrete gravity dam plays an important role in crack propagation and its pattern, because the dam tends to crack before any slippage between the dam and the foundation interface or an occurrence of overturning.
- Considering foundation fault movement in the dynamic analysis of a concrete gravity dam showed that relative fault displacement and its consequences, including induced stresses and crack propagation, can significantly change the dynamic response of the dam. Hence, any foundation fault movement cannot be neglected in analyses.

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