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# NUMERICAL MODELING AND EXPERIMENTAL VALIDATION OF SEISMIC UPLIFT PRESSURE VARIATIONS IN CRACKED CONCRETE DAMS

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## SUMMARY

A theoretical model is developed for transient water pressure variations along tensile seismic concrete crack with known crack wall motion history. Experimental tests are performed to validate the proposed model. The model is then implemented in a nonlinear discrete crack finite element program for seismic analysis of concrete dams. Experimental and numerical results show that water can penetrate in new seismic cracks making them partially saturated over length $L_{sat}$. The $L_{sat}$ and the magnitude of the total water uplift force acting on a crack wall are decreased by crack opening and increased by crack closing. A parametric study of a 90 m gravity dam subjected to sinusoidal base accelerations with different frequencies (1Hz-10Hz) and intensities (0.20g-0.35g) shows that higher frequencies and smaller acceleration amplitudes reduce the developed uplift force in a crack. Transient sliding safety factors (SSF) are computed as dam stability indicators.

## INTRODUCTION

Dam safety guidelines are developed with the objective that concrete dams could suffer cracking and damage during the maximum design earthquake (MDE) but must maintain a stable condition to retain the reservoir. The MDE oscillatory motions could initiate and propagate new cracks in mass concrete or activate opening and closing cycles along exiting lift joints and cracks. Due to dynamic pressure variations at the crack mouth in contact with reservoir, and due to the rapid crack wall motions during an earthquake, the water pressure inside a propagating or an existing crack becomes a transient variable modified from its initial value (zero or hydrostatic condition). An accurate evaluation of seismic uplift pressure along cracks, is one of the most important aspects in stability evaluation of concrete gravity dams during earthquakes. Yet, due to the lack of historical, experimental and numerical evidences, different hypotheses to evaluate seismic uplift pressure along a crack have been retained in dam safety guidelines ranging from

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the full crack mouth reservoir hydrostatic pressure (ICOLD 1986 [1]) to zero pressure (USBR 1987 [2]). Further investigations are thus required to accept, reject, or adapt seismic uplift pressure propositions found in dam safety guidelines depending on numerical test results and related models based on sound theoretical concepts validated by experiments (Javanmardi [3]).

To this end, this paper presents a new dynamic water-crack interaction model implemented in a nonlinear finite element program with gap-friction elements to represent cracks and joints. The model computes the transient crack pressure spatial distribution and magnitude as a function of (a) the crack mouth opening displacement, CMOD(t), and (b) the crack mouth pressure time histories, $P_{crm}(t)$, assuming: (i) 1D flow along the crack, (ii) continuity condition with an incompressible fluid of a constant viscosity, (iii) pressure-flow relations governed by the crack hydraulic conductivity accounting for the crack roughness, laminar or turbulent flow conditions according to Reynold's number, and cavitation, (iv) impervious crack walls, and (v) residual crack aperture during cyclic motions (zero or larger).

A parametric study is performed on a 90m high gravity dam subjected to harmonic ground acceleration to investigate water pressure variations in a crack located at the dam-foundation interface as well as sliding safety factors for variations in (i) the frequency of applied ground acceleration (1Hz to 10 Hz), (ii) the maximum values of crack mouth opening displacement (0.5mm to 2mm), and (iii) the residual crack aperture (0.2mm to 1mm). It is shown that during the crack opening mode, the seismic uplift pressure is significantly reduced along a crack such that downstream sliding safety factors computed, without considering uplift pressures in tensile cracks during the MDE are appropriate.

## REVIEW OF PREVIOUS WORK

Dam safety guidelines formulate the following hypotheses concerning transient seismic uplift pressures (Fig.1):

- <u>Full uplift pressure in cracks initiated during the earthquake</u>: according to ICOLD 1986 [1] "assuming that pore pressure equal to the reservoir head is instantly attained in cracks is probably safe and adequate".

- <u>Unchanged uplift pressure in existing cracks and joints during the earthquake</u>: according to USACE 1995 [4] and FERC 2002 [5] "uplift pressure in cracks and joints should be assumed to be unaffected by earthquake".

- <u>Zero uplift pressure during earthquake</u>: according to USBR 1987 [2] "when a crack develops during an earthquake event, uplift pressure within the crack is assumed to be zero. This assumption is based on studies that show the opening of a crack during an earthquake relieves internal water pressure, and the rapidly cycling nature of opening and closing the crack does not allow reservoir water, and the associated pressure, to penetrate".

- <u>Zero or unchanged uplift pressure according to seismicity conditions</u>: according to CDSA 1997 [6], "in areas of low seismicity, the uplift pressure prior to the seismic event is normally assumed to be maintained during the earthquake even if cracking occurs. In areas of high seismicity, uplift pressure on the cracked surface is assumed to be zero during the earthquake when the seismic forces are tending to open the crack".

USBR 1987 [2] hypothesis is independent of the crack wall motion frequency, while CDSA 1997 [6] introduces the notions of "low" and "high" seismicity that are not clearly defined and are explored in terms of magnitude and frequency of applied ground accelerations and crack mouth opening displacement in this paper.

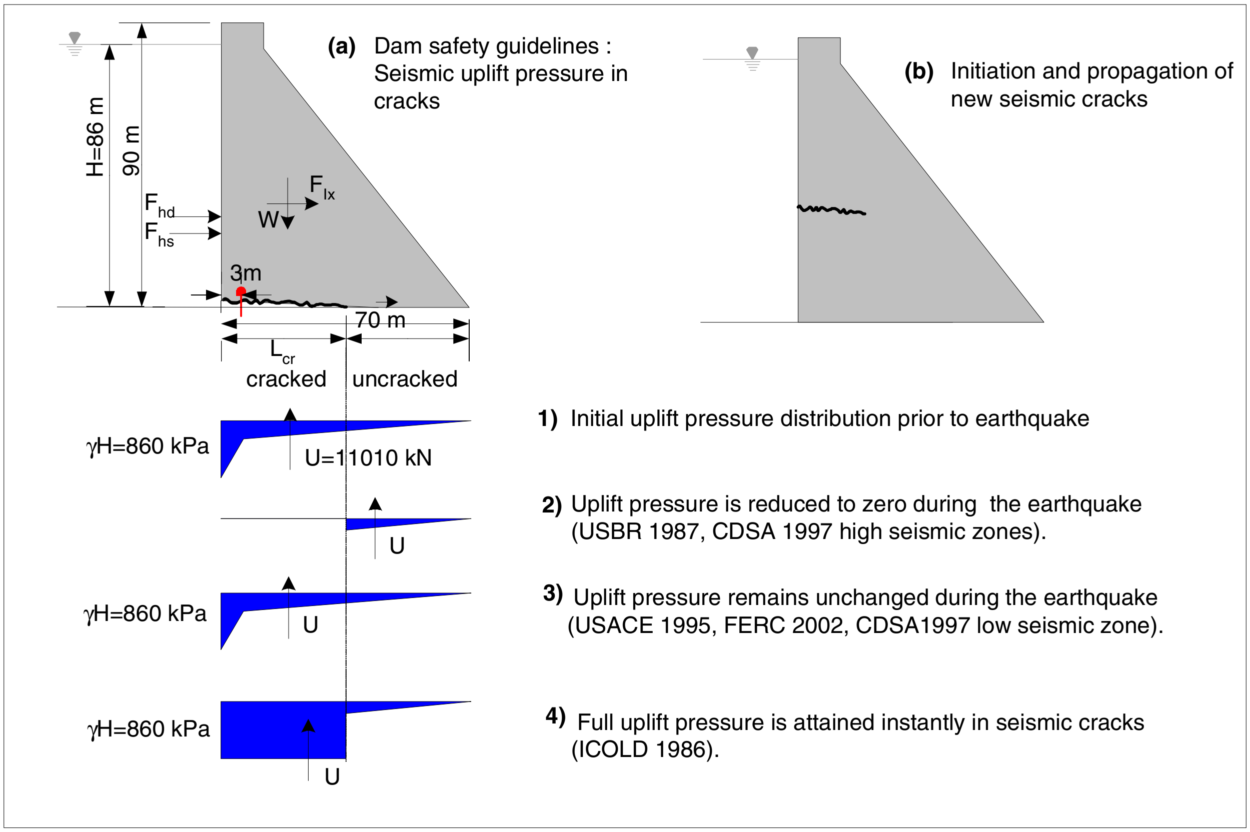


**Fig. 1 Seismic uplift pressure in cracks: dam safety guidelines.**

A rigorous determination of uplift pressure in cracks of concrete dams during earthquakes requires the formulation, experimental validation, and application of an appropriate water-crack interaction model. However, as pointed out by differences in current dam safety guidelines, there is not any universally recognised and validated model to evaluate seismic water pressure variations along moving walls of cracks in a concrete dam. This is due to the complex nature of this fluid-structure interaction problem with moving boundaries. An analytical solution for water pressure variations in an existing crack due to crack wall motions was presented by Tinawi and Guizani [7]. They assumed a water filled existing rectangular crack with constant length, small amplitude crack wall motions (relative to their initial aperture), and one directional laminar water flow to simplify the solution. Based on the proposed formulation, equivalent added masses and damping were derived to be used in finite element computer program. The case study of a 55m high gravity dams subjected to typical earthquake loading indicated that the maximum pressure in a 2m crack along the dam base can be as high as 2 times the hydrostatic pressure and the minimum pressure can be as low as cavitation pressure. Following a simplified numerical modeling methodology, Hall [8] accounted for the transient nature of seismic uplift pressures in smeared crack analysis of arch dams considering that hydrodynamic pressure variations due to dam-reservoir interaction at the upstream face are also acting at the mouths of cracks (joints). It was further assumed that this pressure varies linearly along smeared crack bands across dam sections. No interaction between crack wall motions and related water pressure was considered. It was found that this dynamic internal water pressure effect was able to alter the computed cracking pattern, crack opening and sliding responses. These results indicated the need for further development of seismic water crack-interaction model. Omachi et al. [9] performed a series of shaking table experiments to measure water pressure inside narrow cavities like cracks (30 cm long) inserted in small submerged acrylic blocks (approx. 50 $cm^3$), but no crack wall relative motions (opening-closing) was permitted. These results were used by Zhang and Ohmachi [10] who proposed that the hydrodynamic pressure acting at node i in a horizontal crack filled with water can be expressed as:

$$P_i(t) = [P_{stat} + P_{crm}(t) + \rho\, a_x(t)\, x_{ci}] \qquad (1)$$

where $P_{stat}$ is hydrostatic uplift pressure at crack mouth, $P_{crm}$ is the dynamic crack mouth pressure approximated by Westergaard's theory, $\rho$ is the water density, $a_x$ is the total horizontal dam acceleration at node i , and $x_{ci}$ is the distance between the crack mouth and node i. Seismic smeared crack analysis of Konya dam using the proposed model, assuming that hydrodynamic pressure in cracks develops instantaneously upon cracking, showed that hydrodynamic pressure inside cracks tends to increase the crack length. A basic limitation of this approach is that the effects of crack wall opening and closing motions on the reduction and increase of seismic water pressure were neglected.

Slowik and Saouma [11] measured the developed water pressure along a concrete crack in a dynamic wedge splitting test. They also developed a theoretical model to simulate the test results. The developed model is applicable for the initial crack propagating phase during an earthquake but the subsequent crack closing and opening is not considered. Moreover, this model was not applied in the context of seismic crack propagation and stability evaluation of concrete dams. Seismic water-crack interaction was also investigated theoretically and experimentally by Javanmardi et al. as discussed below [3,12].

## WATER FLOW AND WATER PRESSURE IN PROPAGATING CRACKS

Propagating cracks during earthquakes have oscillatory opening and closing motions. Figure 2 shows a phenomenological description of water flow and corresponding pressure in a propagating crack during its first two successive opening and closing cycles. Neglecting water flow across crack walls (impermeable walls), water exhibits a 1D flow along the crack. Figure 2.a shows the water flow along the crack during its first opening cycle. The existing water pressure at the crack mouth pushes water into the crack and water flow from crack mouth toward crack tip. Water fills a part of the void developed due to crack opening and saturates, partially, the propagating crack. The magnitude of the developed pressure along the saturated length ($L_{sat}$) is not constant. At the crack mouth, it is equal to the reservoir pressure $p_{stat}$, and it is decreasing from crack mouth toward crack tip (pressure losses due to flow) to become equal to the void pressure at the end of the saturated region. The magnitude of the void pressure is determined by the existence of air in the developed void. In a case where there is no air in the concrete, the void pressure decreases to water vapour pressure (cavitation) and water vapour fills the void. If there is some air, from existing air in concrete pores (holes), then depending on the ratio of air to void volume, the void pressure will change between the water vapour pressure and zero.

The volume of void decreases as the crack closing mode begins. The water flow from crack mouth toward crack tip continues during the closing mode as long as the crack closing velocity is small. By increasing the crack closing velocity, the existing water between crack walls is pressurized (like water squeezed between two closing parallel plates). The water flow changes direction. It now flows in two opposite directions form a stagnation point along the saturated part of the crack (Fig. 2.b). The $L_{sat}$ still increases due to water flow from the stagnation point toward the crack tip. The water pressure is maximum at the stagnation point and it decrease from this point toward the saturated region boundaries to become equal to the pressure at these two points. The location of the stagnation point, $L_{sat}$ and the pressure magnitude along the crack are changing with the time and are functions of the crack closing velocity, crack aperture, crack roughness, crack length, and existing crack mouth pressure.

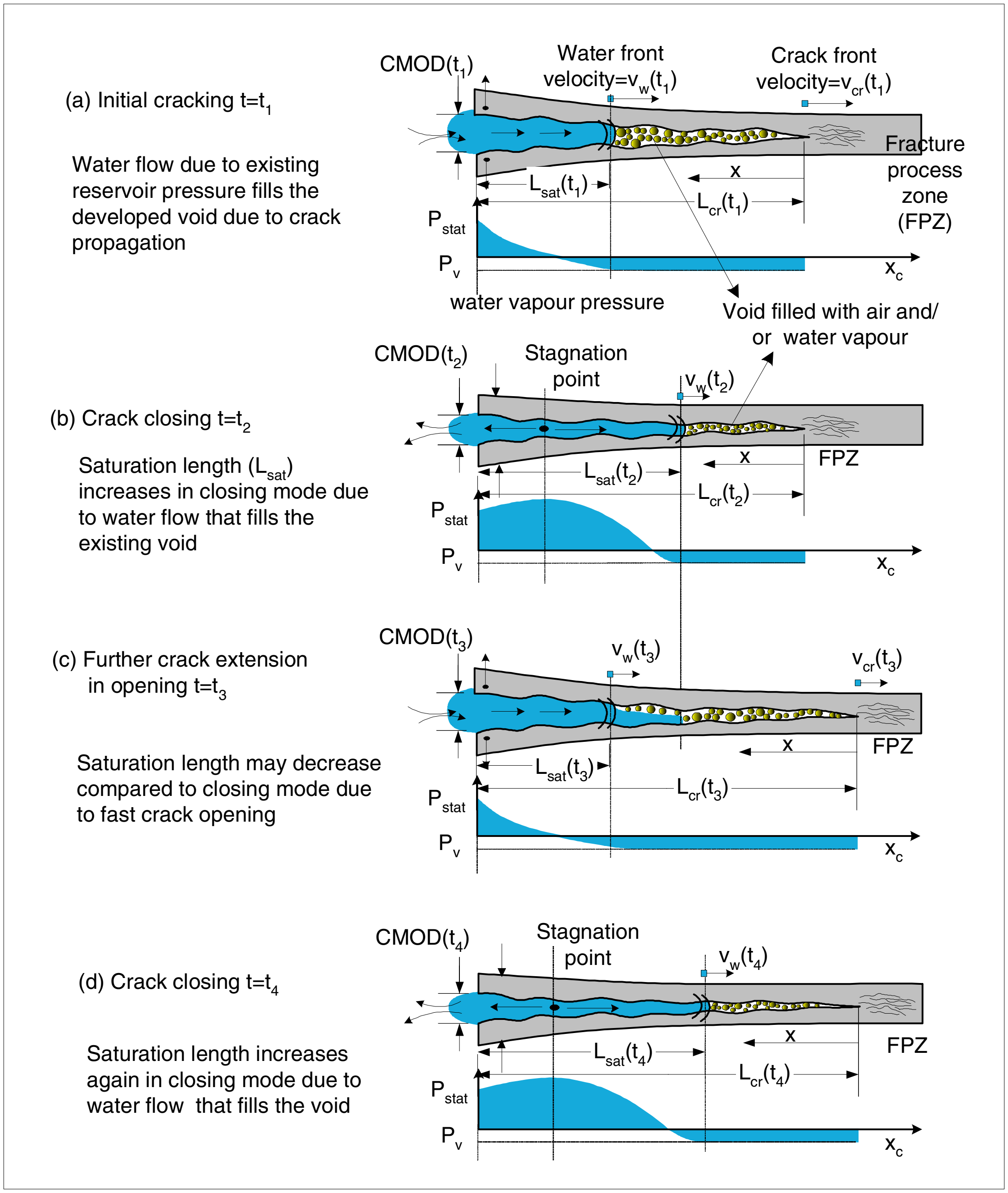


**Fig. 2 Water flow and water pressure along a new crack with oscillatory crack wall motions.**

An important aspect related to water flow in an oscillating crack is that a complete hydraulic closure of a crack is almost impossible. A small space remains between crack walls even after they get in mechanical contact. Compressing crack walls reduces crack aperture, but due to crack wall asperities and the existence of free sedimentary material (from crack wall local crushing of concrete particles), it never becomes zero. A residual hydraulic crack aperture, $u_{res}$, is defined as a function of the crack wall surface geometric properties ($u = u_{mech} + u_{res}$ ; Fig.5). Thus, after mechanical contact of crack walls, a small amount of water exists in the space between the walls.

In subsequent opening cycles, new voids are developing along the crack. Water flow occurs along the crack from crack mouth to crack tip (Fig. 2.c). Water flow can only fills the voids close to the crack mouth, the voids in the rest of the crack remain unfilled and $L_{sat}$ decreases. The only difference between the first opening and subsequent opening cycles is the existence of some water in the residual opening that was already filled due to crack closing. The water flow and corresponding pressure during the second closing cycle is similar to that of the first closing cycle except that there is already some water in the unsaturated region. Therefore, $L_{sat}$ may be longer at the end of the second closing cycle.

## THEORETICAL MODELING

Exact theoretical modeling of the water flow in cracks with moving walls, considering the possibility of cavitation and two phase flow along the crack, is a very complex problem. But with some assumptions, it is possible to formulate a simpler, yet, representative problem. The main assumptions retained herein are that:

- A tapered crack with known crack length, $L_{cr}$, is used to model the crack geometry and rigid body crack wall motions, $(u(x,t)=u(L,t)*x/L)$,
- Crack walls are impermeable,
- Water flow is one dimensional along the crack length,
- There is no significant water flow in the unsaturated part of the crack,
- Water vapour pressure is taken equal to zero,
- The pressure gradient expressions for laminar and turbulent flow, Q(x,t), in the saturated region of a rough crack are (Louis [13]):

$$\left[\frac{dP(x,t)}{dx}\right]_{laminar} = 6\mu\left[1+8.8\left(k/2u(x,t)\right)^{1.5}\right]\frac{Q(x,t)}{u^3(x,t)} \tag{2}$$

$$\left[\frac{dP(x,t)}{dx}\right]_{turbulent} = \frac{\rho}{16\left(\log\dfrac{1.9}{k/2u(x,t)}\right)^2}\frac{Q^2(x,t)}{u^3(x,t)} \tag{3}$$

where $\mu$ is the water dynamic viscosity, u is the crack aperture, k/2u(x,t) is the relative crack roughness (taken as 0.5 for rough concrete tensile cracks), and $\rho$ is the water mass density.

A subroutine called DUP_CRACK is developed for numerical integration of Eqs (2,3) along the crack saturated length, while the flow continuity and pressure compatibility are satisfied. Using this subroutine, water pressure variations along a crack with known crack wall motion history u(x,t), crack mouth pressure $P_{crm}(t)$ (equal to the hydrostatic value $P_{stat}$ or to the hydrostatic plus hydrodynamic values), and crack length ($L_{cr}$) can be computed. This subroutine is applicable for new cracks as well as initially saturated existing cracks.

## EXPERIMENTAL PROGRAM

Experimental tests were performed to measure water pressure along concrete cracks with moving walls. The concrete specimens and test set up are shown in Fig. 3. The concrete specimens (0.15 m x 0.55 m x 1.5 m) are fixed to a very stiff steel supporting structure and are attached to the shake table by a rigid link to apply displacements. A small notch was created in the specimens during pouring of concrete to induce a crack at a certain level. A small steel tank was added in front of the notch to approximately model the reservoir in a real dam. An additional water tank pressurised with an air compressor is used to provide the desired static pressure in the notch. A thin waterproof membrane is glued to the concrete surface around the notch and the expected crack path. Four holes, that intercept the estimated crack trajectory, were used to measure the pressure from pressure transducers (PT) at the top of the specimens. Using this experimental set up, five new specimens are tested. Water pressure variations along the propagating crack and subsequent closing and opening harmonic motions are measured. Letting the cracked specimens be completely saturated, more than 220 tests have been done. Harmonic oscillatory displacement control tests with different frequencies, crack opening displacements and crack mouth pressures were performed. Existing crack and new crack test results are used to validate the proposed theoretical model.

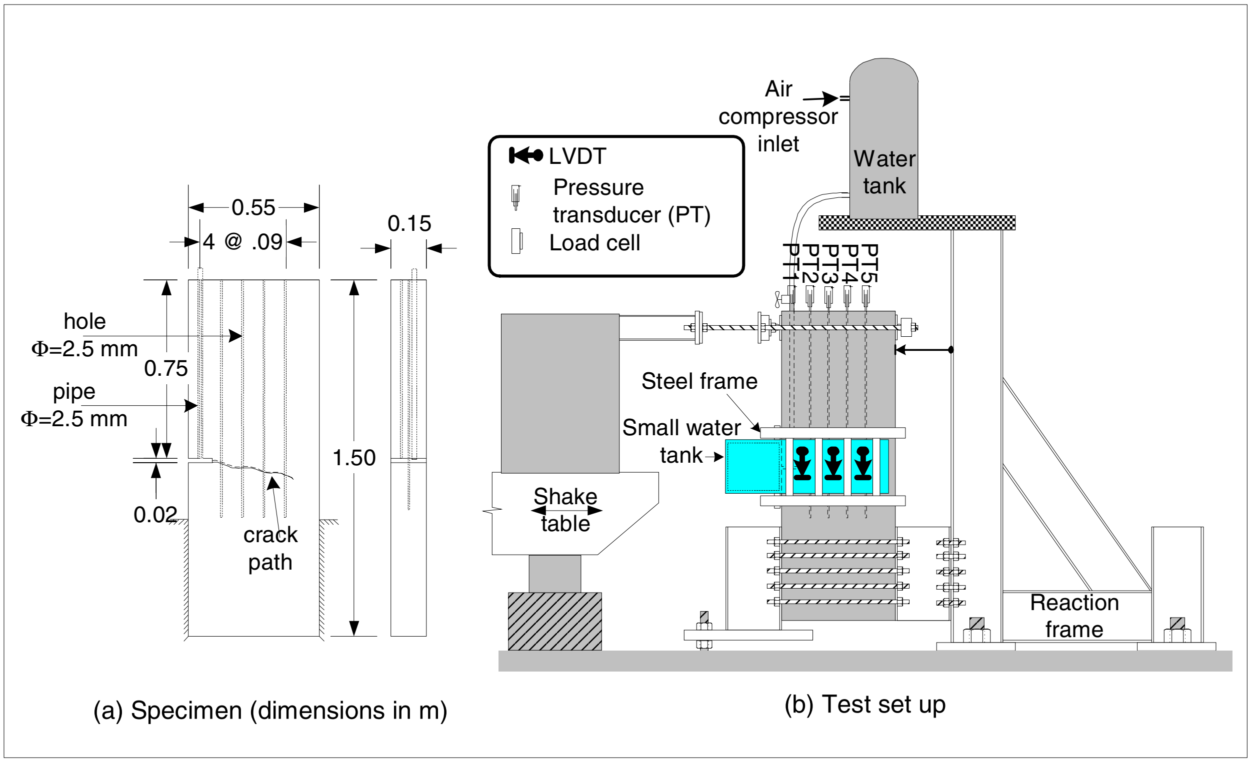


**Fig. 3 Typical specimen geometry and experimental test set up.**

Figure 4.a shows the measured pressure as well as computed pressure for a new crack test ($P_{crm}$=100kPa, f=2Hz). Initially in the absence of a crack, the pressure in all PT is zero. The pressure drops in PT2, PT3, and PT4 during the crack initial propagation confirms the development of voids along a length, while the unchanged pressure in PT5 (zero) shows that this hole is not yet crossed by the crack. The minimum normalised pressure in this case is -60 kPa. The observed high frequency pressure oscillations in PT3 are due to air bubble collapse confirming the occurrence of cavitation. Replacing the measured PT3 response by an equivalent smoothed pressure variation, and neglecting the differences for the region of negative pressure (cavitation) that comes from the zero pressure assumption for cavitation in computed results, the computed pressures are similar to the measured pressures.

The water pressure profiles along the crack for four different stages of crack motion, including cracking (t=2.69 sec), first closing (t=2.85 sec), second opening (t=3.03 sec), and second closing (t=3.35 sec) are shown in Fig 4.b. During the test, PT1 ($P_{crm}$) exhibits some variations due to opening and closing of the notch and the water tank. To eliminate this pressure variation effect, the measured pressures are normalized such that $P_{crm}(t)$ remains unchanged (100kPa). The measured pressure profiles along the crack are basically similar to the corresponding phenomenological pressure profiles shown in Fig 2. More detailed evaluation of computed results applying the proposed model have shown that they are generally in good agreement with the new and existing crack test results (Javanmardi [3,12]).

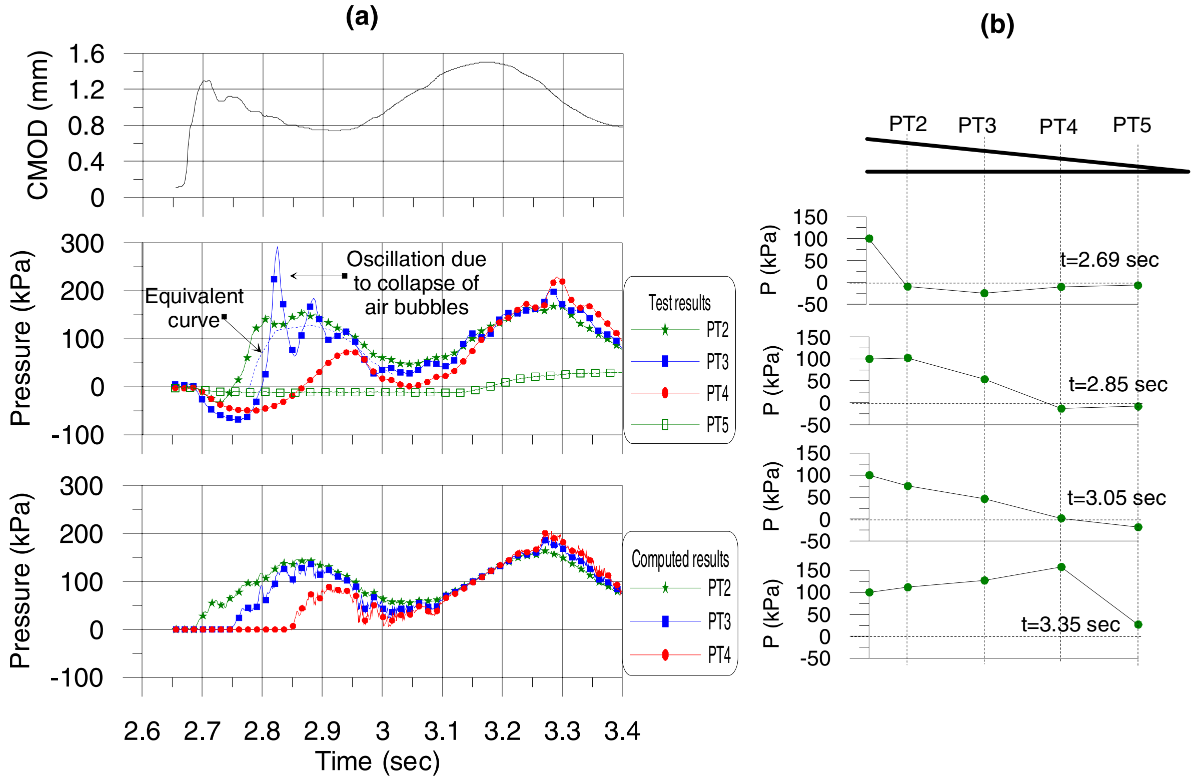


**Fig. 4 Computed and measured results for a typical new crack test ($P_{crm}$= 100 kPa, f=2 Hz).**

## FINITE ELEMENT ANALYSIS OF DAM CONSIDERING DYNAMIC UPLIFT PRESSURE

In a simplified approach, to compute the uplift pressure along a seismic crack in a concrete dam, an uncoupled hydro-mechanical analysis may be utilized. The CMOD time history response could be determined by a discrete crack finite element analysis ignoring transient water pressure variations and then used as input data in the proposed crack-water interaction model. However, water pressure variations inside the crack modify crack wall motions and an uncoupled hydro-mechanical analysis is not realistic (at least in closing mode, as it will be shown later). It is thus required to adjust the computed CMOD response while considering dynamic water pressure variations in the crack by an iterative procedure. A coupled water-crack interaction model was thus implemented in INTRFACE, a finite element computer program for seismic analysis of gravity dam using discrete gap-friction elements to model cracks and joints (Fronteddu [14]).

The dynamic equilibrium equations of the dam subjected to seismic excitation are expressed as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+\{R\}=-[M]\{r\}\{\ddot{u}_g\}+\{f_{stat}\} \tag{4}$$

where [M] is the mass matrix, [C] is the damping matrix, {R} is the restoring force vector, $\{f_{stat}\}$ is the vector of pre-seismic applied force, $\{u\}$, $\{\dot{u}\}$, $\{\ddot{u}\}$ are displacement, velocity and acceleration vectors, respectively, $\{\ddot{u}_g\}$ is the vector of ground acceleration, and {r} is the unit vector specifying the active dynamic degrees-of-freedom. The dynamic water pressure in a crack, expressed as a force vector{Wpr}, can be treated as an additional restoring force in Eq. (4) that can be written as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + \{R + Wpr\} = -[M]\{r\}\{\ddot{u}_g\} + \{f_{stat}\} \tag{5}$$

The $\alpha$ integration method was adopted herein to integrate Eq. (5) for the cracking analysis of gravity dams using gap-friction elements. The restoring force and water pressure force are functions of the gap elements relative displacements that are not known a priori during the integration such that an iterative procedure is required to solve Eq. (5). The modified Newton-Raphson method is used for iterations in each mechanical time step.

Due to the rapid increase in uplift pressure in crack during the closing mode, it was found that the iterative solution procedure exhibit sometimes a convergence problem (especially for initially saturated cracks). This problem is similar to a mechanical impact where huge contact forces develop at contact time leading to high frequency motions subsequently appearing in the displacement (velocity) response and perturbing water pressures. This problem needs further investigation to develop a robust numerical solution procedure. However, numerical investigations have indicated that water-crack interaction could be properly modeled for potential discontinuities (cracks) that are initially in an unsaturated condition being initiated and subsequently propagated by the earthquake.

Hydrodynamic dam-reservoir interaction increases or decreases water pressure on the upstream face and the crack mouth in contact with the reservoir. Herein, the Westergaard approach is used to represent this additional pressure:

$$P_{west}(t) = \frac{7}{8}\rho H\left(1 - \frac{y}{H}\right)^{1/2} \ddot{u}_g \tag{6}$$

where $\rho$ is the mass density of water, H is the height of reservoir, y is the crack mouth height from the bottom of the reservoir, and $\ddot{u}_g$ is the horizontal earthquake ground acceleration. The crack mouth pressure ($P_{crm}$), for water pressure computations along the crack is then computed from:

$$P_{crm}(t) = P_{stat} + P_{west}(t) \tag{7}$$

## TRANSIENT SEISMIC WATER PRESSURE IN CRACKED DAM

To investigate water pressure variations in successive opening and closing of cracks during earthquake, a typical 90 m gravity dam section subjected to very low frequency sinusoidal base acceleration (f =1Hz) with a peak ground acceleration PGA=0.20g is first analysed. Low frequency motions promote water penetration in the crack. The dam geometry and the assumed concrete properties are shown in Fig. 5. Gap elements are located along the dam-foundation interface to model crack propagation. The structural response of the dam is first computed assuming zero initial uplift pressure (dry condition), the computed crack length is 14 m. A coupled analysis with dynamic water pressure along the crack is then performed (wet condition) leading also to a crack length of 14 m. A 0.5 mm residual opening is assumed. Figures 6.a,c,e show CMOD for these analyses and uplift forces (pressures) from the coupled hydro-mechanical (wet) condition. Figures 6.b,d,f show these response quantities in more details for the last two sec.

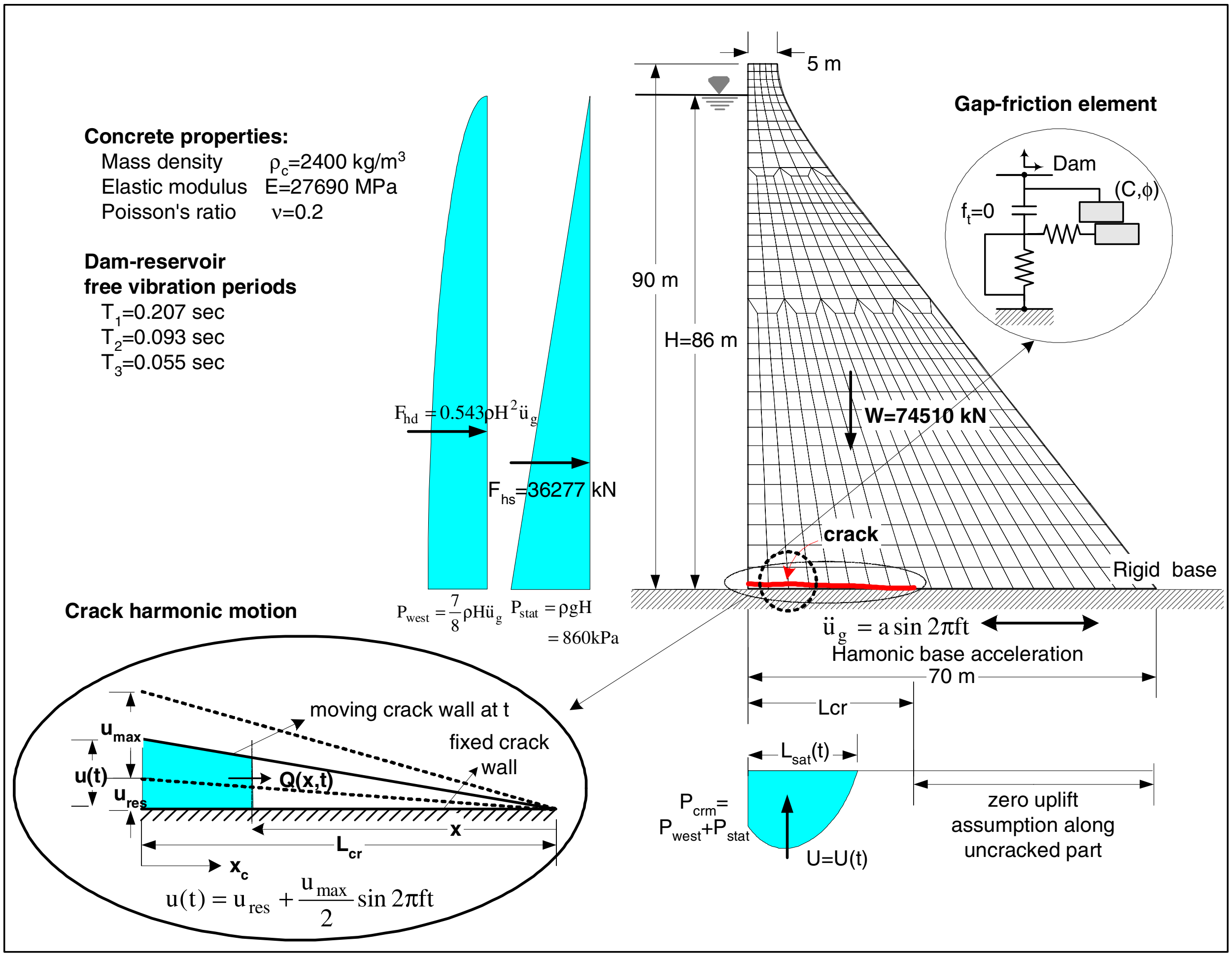


**Fig. 5 Typical 90 m dam for applications.**

Comparisons of CMODs show that the opening responses are similar for dry and wet conditions but that the closing responses are different. The uplift force during the opening mode is so small that it does not affect the crack opening response but the uplift force increases as crack closing starts. The uplift force in closing mode is considerably larger than the uplift force in opening mode. This uplift force build-up slows down the crack closing velocity (slope of CMOD curve) and changes the crack closing response. However, the uplift force is not large enough to prevent crack walls from mechanical impact. As soon as two crack walls hit each other, the crack closing velocity is instantaneously reduced causing a significant decrease in water pressure along the crack. Water pressure variations become almost linear along the crack saturated length as along as crack walls remains in contact.

Pressure variations along the crack (Fig. 6e) show the water penetration (pressure build-up) along the crack in successive crack opening-closing cycles. Figure 7, representing the 3D pressure variations along the crack, illustrates this phenomenon more clearly. The saturated length ($L_{sat}$) increases from 0.0m to 4.6m. Water pressure variations from 2 sec to 4 sec and from 8 sec to 10 sec are also shown in more details in Figs 7.b,c. Although the magnitudes of uplift pressure and $L_{sat}$ in closing mode are different, pressure variations during opening are similar. This is an important aspect that was used to derive a simplified method for seismic uplift pressure evaluation in opening crack mode (Javanmardi [3]).

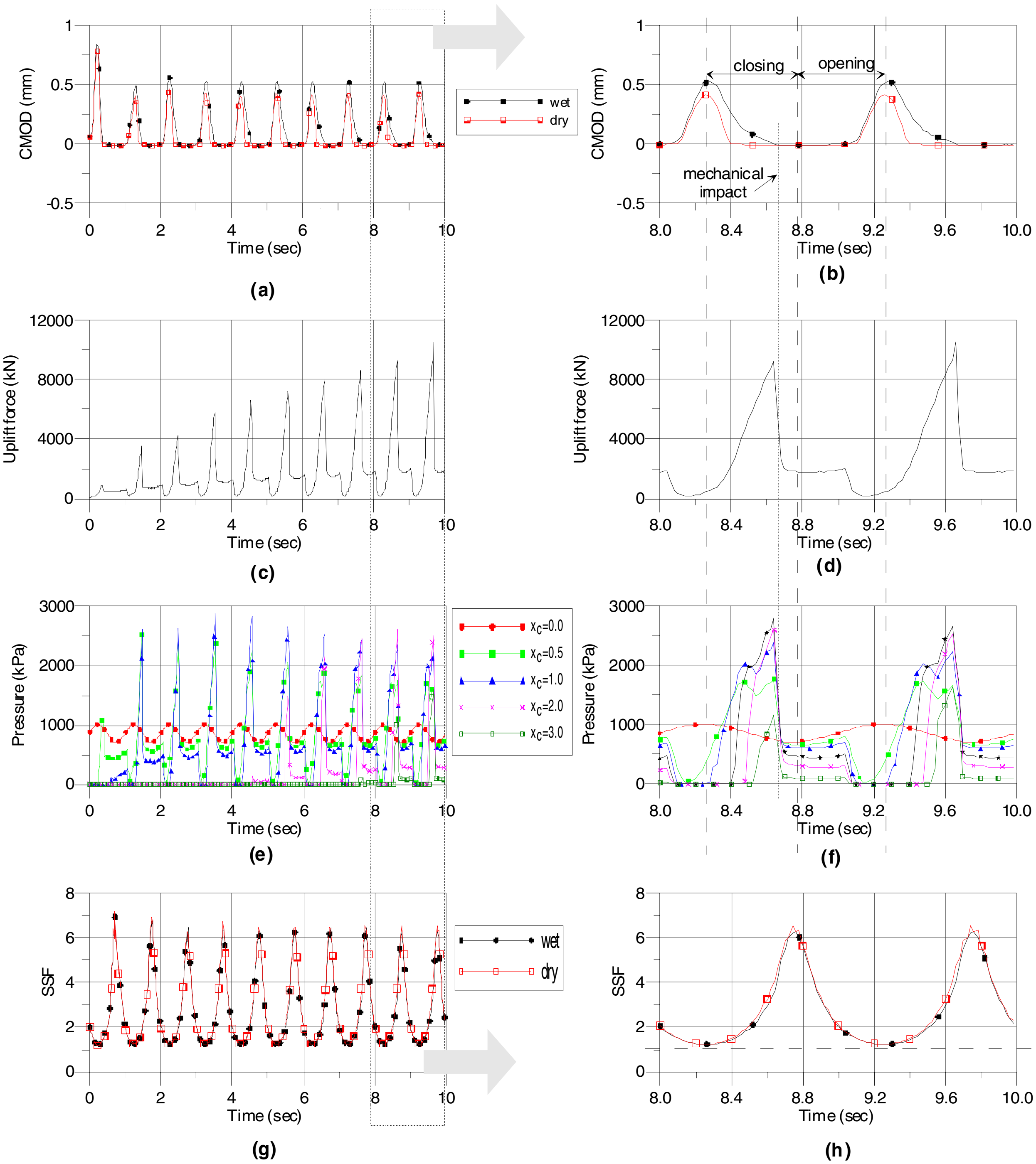


**Fig. 6 Coupled analysis of a 90 m dam subjected to a sinusoidal base acceleration.**

($\ddot{u}_g(t) = 0.2g\sin 2\pi ft$ **; f=1 Hz**)

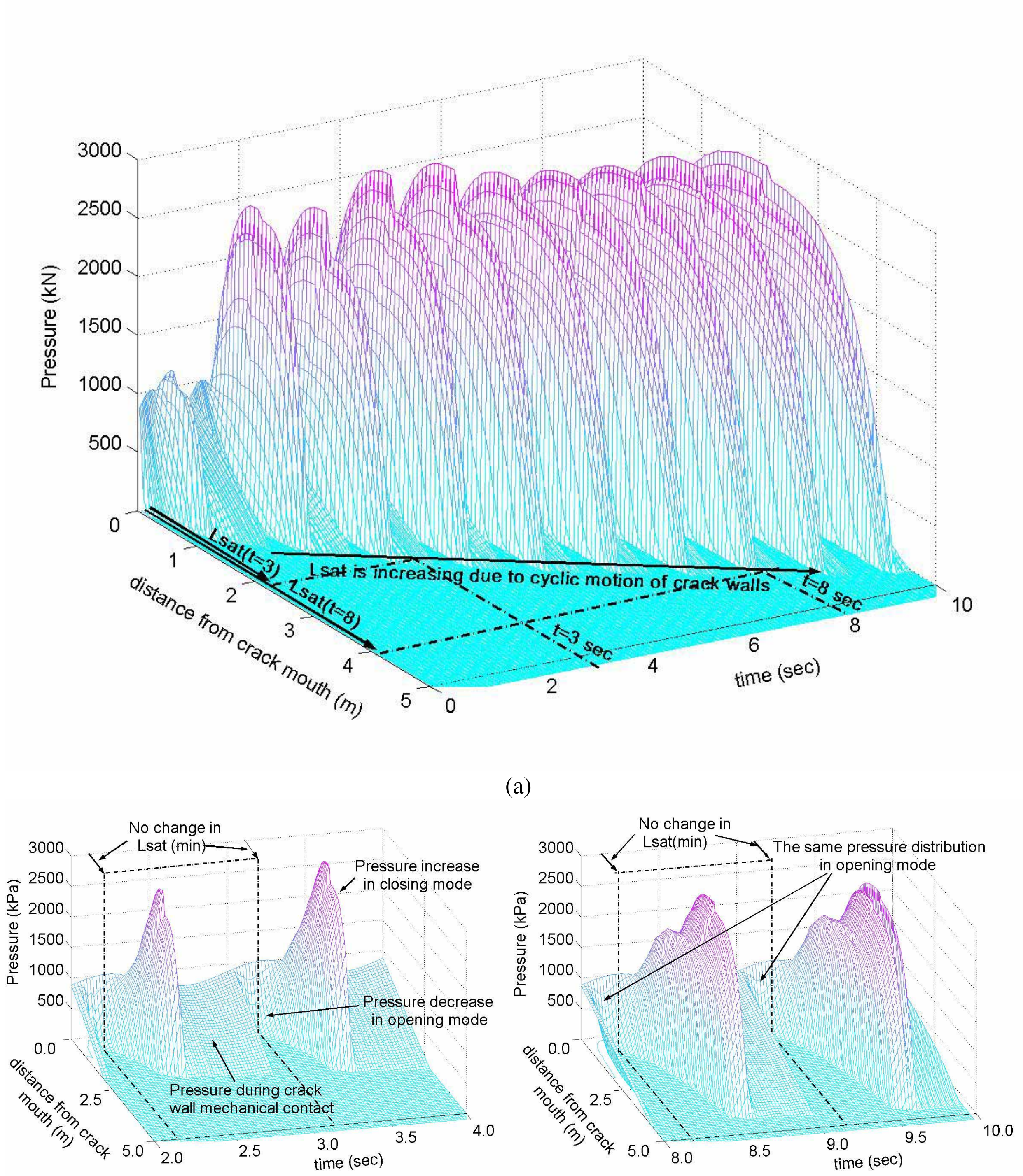


**Fig. 7 Three dimensional presentation of pressure variations along the crack of a 90 m dam subjected to sinusoidal base acceleration** ( $\ddot{u}_g(t) = 0.2g \sin 2\pi ft$ **; f=1 Hz).**

## DAM SLIDING STABILITY

Sliding stability under seismic excitations is one of the most important concerns for gravity dams. It is important to investigate the effect of dynamic uplift pressure variations on the sliding stability of gravity dam. In the absence of cohesion, a transient evaluation of the sliding safety factor (SSF) could be defined as:

$$SSF(t) = \frac{\mu . \sum V(t)}{\sum H(t)} \tag{8}$$

where $\mu$ is friction factor, $\sum V(t)$ is summation of vertical forces acting on the dam (including uplift pressure), and $\sum H(t)$ is summation of horizontal forces acting on the dam. SSF(t) becomes a useful indicator of sliding stability to compare different seismic uplift pressure modeling assumptions. Assuming that $\mu$=1.0, SSF (t) is thus computed for the dry and wet crack conditions as explained before. The results are shown in Figs 6.g,h. SSF from wet and dry analyses in Fig 6.h are basically similar for the heel crack opening mode. This is the critical condition for sliding stability as hydrostatic, hydrodynamic and concrete inertia forces are all pointing in the downstream direction. The developed uplift force during the crack opening mode considering the water-crack coupling effect is so small that it does not change the computed SSF as compared to the dry condition. The increase in uplift force during the crack closing mode slightly reduces the SSF (wet condition) compared to SSF with a dry condition. However, SSF during crack closing are still much larger than SSF during the crack opening mode because during crack closing the concrete inertia (hydrodynamic) forces are pointing in the upstream direction while the hydrostatic force is pointing downstream.

## PARAMETRIC STUDY

According to the proposed model, the major parameters that affect the magnitude of seismic pressure in a crack of a gravity dam subjected to sinusoidal base acceleration are: (i) the maximum crack opening $CMOD_{max}$, (ii) the residual crack opening $u_{res}$, (iii) the crack oscillating frequency f. A series of analyses have been done to investigate the effects of these parameters on the seismic uplift pressure at the base of the 90 m dam of Fig. 5. Harmonic base accelerations at 1 Hz and 10 Hz with PGAs adjusted to produce crack wall motions with CMODs equal to 0.5mm and 2 mm are considered (Table 1). The analyses are performed over the necessary duration to reach a steady state uplift force; the 1 Hz excitation case is analyzed for 10 sec, while the 10 Hz case is analyzed for 4 sec. For hydraulic computation, three different residual openings ($u_{res}$; 0.2, 0.5, and 1.0 mm) are considered. The results including (i) the maximum closing pressure, (ii) the maximum uplift force in the crack, (iii) the maximum $L_{sat}$ in closing mode, (iv) the minimum $L_{sat}$ in opening mode, (v) the minimal value of $SSF_{min}$, and (vi) the crack length are summarized in Table 1. Comparisons of the results lead to the following conclusions:

- Effect of maximum crack opening, $CMOD_{max}$ : By increasing $CMOD_{max}$ the closing pressure and maximum $L_{sat}$ in closing mode are increasing (for a constant frequency, an increase in $CMOD_{max}$ increases the crack closing velocity producing larger water pressure). The magnitude of the maximum uplift force in closing mode is also increasing. The magnitude of crack opening in a gravity dam subjected to earthquake loading depends on the earthquake intensity. Therefore larger dynamic uplift forces are expected in cracks of concrete dams during the earthquake as its intensity increases. However, even for very low frequency motions and large CMOD with long time period for water penetration, the results indicate that heel tensile crack opening (coinciding with critical downstream sliding condition) reduces the uplift forces to a negligible value.

- Effect of frequency of crack motion, f: Due to increase in crack motion frequency from 1Hz to 10 Hz, the maximum closing pressure increases locally. But due to a reduction in crack saturation length the maximum uplift force during high frequency closing mode decreases. Therefore the developed uplift forces in concrete gravity dams subjected to earthquake ground motions with high frequency content are smaller compare to uplift forces in concrete dams subjected to ground motions with lower frequency content.

- Effect of residual crack opening, $u_{res}$: By increasing $u_{res}$, the magnitude of seismic uplift pressures decreases but the magnitudes of the uplift forces remain almost unchanged due to the increase in crack saturation length. Therefore, the developed uplift force along the crack is not very sensitive to the assumed residual crack opening.

**Table 1 Parametric analysis results of 90 m dam subjected to sinusoidal base acceleration.**

| | f=1 Hz, PGA=0.20 g ,<br>$CMOD_{max}$=0.5 mm<br>$CMOV_{max}$=3.1 mm/sec | | | f=1 Hz, PGA=0.32 g ,<br>$CMOD_{max}$=2.0 mm<br>$CMOV_{max}$=12.6 mm/sec | | | f=10 Hz, PGA=0.35g ,<br>$CMOD_{max}$=0.5 mm<br>$CMOV_{max}$=31.4 mm/sec | | |
|---|---|---|---|---|---|---|---|---|---|
| | $u_{res}$ 0.2mm | $u_{res}$ 0.5mm | $u_{res}$ 1.0mm | $u_{res}$ 0.2mm | $u_{res}$ 0.2mm | $u_{res}$ 1.0mm | $u_{res}$ 0.2mm | $u_{res}$ 0.5mm | $u_{res}$ 1.0mm |
| Max closing press. (kPa) | 2800 | 2600 | 2000 | 6000 | 4500 | 3000 | 10000 | 6000 | 3500 |
| Max closing uplift (kN) | 10500 | 10500 | 9000 | 15000 | 14000 | 14000 | 5500 | 6000 | 6000 |
| Max saturation length (m) | 3.08 | 4.66 | 5.95 | 4.52 | 5.79 | 6.79 | 1.05 | 1.89 | 2.66 |
| Min saturation length (m) | 0.35 | 0.70 | 1.19 | 0.21 | 0.42 | 0.70 | 0.1 | 0.14 | 0.35 |
| Min opening uplift (kN) | 120 | 200 | 350 | 50 | 160 | 220 | 36 | 50 | 80 |
| Max crack length (m) | 14 | 14 | 14 | 28 | 28 | 28 | 14 | 14 | 14 |
| % Cracked base | 20 | 20 | 20 | 40 | 40 | 40 | 20 | 20 | 20 |
| $SSF_{min}$ (downstream) | 1.2 | 1.2 | 1.2 | <1.0 | <1.0 | <1.0 | 1.35 | 1.35 | 1.35 |
| Dry crack: % Cracked base | 20 | | | 40 | | | 20 | | |
| Dry crack: $SSF_{min}$ | 1.2 | | | <1.0 | | | 1.35 | | |

According to the results of all analyses, the saturation length in crack opening mode is small compared to the length of crack. The developed uplift force in crack tensile opening mode is so small that the minimum SSF of the dam in a wet condition is not affected by the developed uplift force.

## SUMMARY AND CONCLUSION

A theoretical model is developed to compute uplift pressure variations along concrete cracks with moving walls. Experimental crack test data are used to verify the proposed model. The model is implemented in a finite element computer program for dynamic analysis of gravity dams considering hydro-mechanical water-crack coupling. The results of analyses of a typical 90 m dam subjected to low (1Hz) and high frequency (10Hz) sinusoidal base accelerations show that water can penetrate into part of a seismically initiated crack and saturates it partially. During the crack opening mode the saturated length is small (from few centimetres to few meters depending on the opening velocity, magnitude of the opening and crack mouth pressure). Water pressure decreases along this length from crack mouth pressure to the existing void pressure at the end of the saturation length. The developed uplift forces are small and the modeling assumption of zero uplift pressure in a seismic crack in tensile opening mode appears to be justified.

The maximum crack opening and frequency of crack oscillatory motions have the most important effects on the magnitude of seismic uplift force in closing mode, while the assumed residual crack opening does not change it significantly. The saturation length and the uplift force in crack closing mode are increasing in successive cycles to reach a steady state. The maximum pressure can be very high locally and the saturated length can be increased up to several meters, still smaller than the crack length. Because the pressure tends to develop in a region close to the crack mouth, detrimental effects for the global dam stability are unlikely to occur (ex. wedge effect propagating a crack filled with water as it closed). It is shown than the seismic uplift force during the heel crack opening mode is very small relative to the dam weight. Based on the limited experimental and numerical evidences presented in this paper, and pending further investigations, it appears that the critical SSF of the dam against downstream sliding could thus be computed by considering zero uplift pressure in the crack region subjected to tensile opening.

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