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INFLUENCE OF SITE GEOLOGY ON THE SEISMIC BEHAVIOR OF CONCRETE DAMS

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ABSTRACT: In seismic zones, arch dames are the most feasible when the geology and the integration of ancillary structures allow it. Arch dams postpone the hydrostatic push on the foundation by bows (under compression). It is the slenderness of the valley, the geometry of the arch, and the contrast of rigidity between the concrete and the rock that determine the behavior of the structure. The stability of this type of dam differs essentially from that of gravity dams, which results from a certain inequality between the flow of water and the weight. An intermediate design combination between the two; gravity and arch profiles is the arch-gravity dam, which takes advantages of each type of dam. The failure of this type of structure under earthquakes is generally accompanied by dramatic damage on both human and material sides. Consequently, it is important to study in a reliable and precise way their dynamic behavior considering the impact of the geology of the site, which plays an important role on the profile to be adapted and on the seismic response of the structure. The purpose of this paper is to carry out a comparative analysis between the gravity dam response and the single and double curvature arch dam response with variable site conditions. A finite element numerical modeling using the Cast3M code is performed to analyze and evaluate the vulnerability of each profile design. Proportionality is deduced between the displacement of the crest and the rock type on the one hand, and between the crack opening evolution and the rock deformation modulus, on the other hand.

Key Words: Dams, Dynamic behavior, Modeling, Cracking

1. INTRODUCTION

The prediction of the behavior of dams under dynamic solicitations is a very important issue in the evaluation of their security in seismic zones. Beyond the notion of "mechanical resistance" usually required, it is necessary to study how to deal with their dynamic behavior reliably and accurately by considering the pathological phenomena that may occur during their life cycle: cracking, interaction phenomena (THM …), effects of the site,…etc.

One of the first computer programs based on the finite element method for the seismic calculation of dams were developed by [1] where a model of rock and foundation without mass with ignorance of the influence of water on the seismic response of the dams has been adopted. On the basis of this model, many studies on the influence of hydrodynamic effects with mass approximations on the seismic response of dams were developed [2][3]. This program considers the hydrodynamic effects of water with compressibility and the effects of absorption of tank boundaries. An analytical method based on time history analysis has been proposed in [4] to examine the dynamic interaction of rock-foundation-damming and material nonlinearity.

A case study of the BIMOUNT dam was carried out by [5] in order to understand and cope with the lifetime behavior of the dam-related to the swelling of concrete. Further works done by [6] were specifically carried out on three examples of arch dams; a coupling approach based on monitoring instrumentation/numerical modeling has been implemented not only during the design phase but also in the construction phase respectively for the dams of Katse, Puylaurent and the dam of Maury.

A computation-measurement comparison made it possible to discover several uncertainties inducing different calculations of adjustment related to the variation of the deformation modulus of the rock and concrete to be able to reflect the "real" behavior of the dam and to guide thereafter the comfort project.

The long-time behavior of dams requires refined analysis. Numerical-modeling-based approaches are very useful to understand and quantify the irreversible evolution observed, such as the swelling of concrete, shrinkage, creep, etc. [7]. Other works have been achieved regarding the long-term's behavior in [8] on forty-six dams. The analysis is devoted to the comparison of the evolution observed in keys of arches under conditions of filling and identical thermal conditions and the evaluation of the orders of magnitude of irreversible evolution in order to establish a relation between the different causes possible and the irreversible movements. In these studies, the effect of seismic actions has not been taken into consideration. A finite element dynamic computation model has been proposed by [9] for a time history analysis of reservoir-gravity dam systems taking into account the hydrodynamic interaction effects. Other authors [10] proposed stochastic models with spatiotemporal variability of seismic movement; these models are based on the spectral representation method developed by [11]. A relationship between the intensity measurement (like the spectral acceleration) and the displacement-crack ratio is elaborated by [12] to deal with a probabilistic seismic model on the concrete dams.

The present paper is a contribution to the comprehension of dam's behavior under seismic solicitations. It aims at a numerical study based on a finite element modeling process to better understand the dynamic behavior of the Koyna dam [13]. Various modulus of the deformation of the rock and different forms of dam profiles are investigated. The profiles were analyzed in order to optimize the concrete volume according to safety criteria. For this purpose, an elastoplastic model coupled with anisotropic damage initially developed by [14] is adopted to model the behavior of the dam-foundation system. The presentation of the crack parameters in space (opening, propagation…) is performed using an energy approach proposed in [15][16].

The main objective is to conduct a dynamic time history analysis on the gravity-form Koyna dam and compare its seismic response to the responses of single-and double-curvature arch dams, arch-gravity returned with different geological conditions of the rock.

2. PROBLEMATIC

The knowledge of the morphology of the valley is paramount in the choice of the type of dam. In fact, two topographic parameters influence the choice of the type of dam; the shape of the valley (in U or V) on the one hand, and the relative width (L/H), also called slenderness, on the other hand. In general, a wide valley will be suitable for the construction of an embankment dam, against a narrow site and will be suitable for a gravity dam or arch provided that the foundations allow it. In general, a wide valley will be suitable for the construction of an embankment dam.

Furthermore, regional seismicity is a necessary factor to consider in the design of dams. Arch dams or gravity dams have relatively high strengths, especially if the foundation rock and banks present a considerable deformation modulus. The improvement of the resistance against this kind of excitation is done either by the filling of the joints by cement slurry if it is about a gravity dam, or by widening of the souls of contention downstream for the dams with a buttress.

For arch dams, the horizontal strengths are transferred from the center to the banks by the effects of arches, however, the vertical strengths are transferred to the shore by the hull stiffness. In the vertical direction, the consoles take part of the hydrostatic loading in bending and shear. From bank to bank, the hull stiffness causes a plunge of efforts towards the rivers and, consequently, a tendency to raise the central consoles. This second hyperstatic phenomenon aggravates the resistance' conditions of the base of the central consoles.
In addition to all these considerations, the aspect related to the economic feasibility of concrete dams arises in a relevant way. Scientific developments are attempting to optimize the profile of concrete dams in order to gain considerable volumes of concrete and ensure acceptable safety criteria, especially under seismic solicitations.

3. RESEARCH SIGNIFICANCE

The stability of the arch dams differs essentially from that of the gravity dams, which results from a certain inequality between water flow and weight. The resistance mechanisms of dams against horizontal and vertical stresses induce kinematic variations that may affect their stability. The maximum radial displacements (in key and crest) are the most significant and must be systematically studied, as well as the tangential shifts of the rivers, which make it possible to evaluate the influence of the movements of the supports on the structure.

To meet all these varied and conflicting design criteria, a nonlinear dynamic analysis with a variation of rock deformation modulus (between 3 and 15 GPa) is performed on a gravity dam profile at first. Then, "with equivalent dimensions", two other profiles of dams (arches and arch-gravity) are subjected to a similar analysis in order to compare the seismic response of the latter with that of a gravity dam. Moreover, the seismic response of a double curvature arch dam is studied to quantify the contribution of the double curvature on the dam response in terms of displacement, damage and cracking as well as on the optimization of the concrete volume.

4. TOOLS AND METHODOLOGY

4.1 Characterization of the Profiles of Dams

Based on the conceptual criteria of design for gravity and arches dams, table 1 gives the main design criteria for numerical modeling.

Table 1 Description and geometry of the profiles of the dams analyzed

Profiles	f	$\mathbf{E_b}$	$\mathbf{E_c}$	R	H
G.D	0.7	70	14.8	/	103
S.C.A.D	/	48	08	271.6	103
S.C.A.D	/	55	09	290.6	103
A-G	/	60	10	297.4	103
D.C.A.D	/	08	48	271.6	103

Where:
F: the downstream leak. $\mathbf{E_b}$: Thickness in basethe (m)
$\mathbf{E_c}$: Crown thickness (m).
R: Curvature radius (m). H: Height (m).
G.D: Gravity Dam.
S.C.A.D: Single Curvature Arch Dam.
A-G: Arch-Gravity.
D.C.A.D: Double Curvature Arch Dam.

4.2 Geological Considerations

Geology of the site and the soil resistance are decisive parameters in the choice of the dam profile. Concrete dams, unlike earth dams, require rather a high deformation modulus of the rock.
Principally, it is essential to avoid the installation of a concrete dam on the poor and deformable soil in order to prevent any probable settlement of the dam under the action of its own weight, on the one hand, and the destabilizing effect of water infiltration under foundation, on the other hand. Particularly for gravity dams and arch dams, the deformation modulus of the rock has a great influence on the design and behavior of the structure. For this purpose, during the numerical modeling process, a variation of the modulus of deformation of the rock (between 3 and 15 GPa) is considered to take into account the effect of the geology of the site in the response of the dam to a seismic excitation. An analysis of the behavior of the conceptual profiles of the dam under different loads has been parameterized in relation to the variations of the deformation modulus of the rock. These parametric analyses were guided by the study of the evolution of displacements and crack openings at the base.

4.3 Modelling

Finite element modeling under the CasT3M finite element code [18] is developed to study the dam-foundation system. An elastoplastic model with anisotropic damage initially developed in [14] is adopted not only to model the behavior of the dam but also of the rock.

As a seismic signal, the system is subject to an earthquake recorded at the Koyna seismic station. (INDIA), shown in Fig 1.

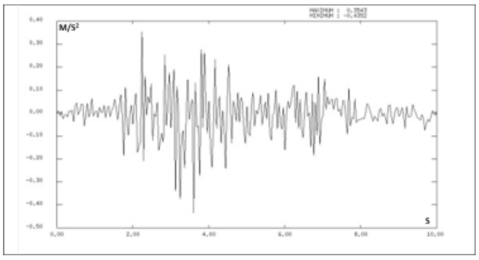

Fig. 1. Koyna Seismic Acceleration (INDIA)

Table 2 summarises the different values of the parameters of the materials considered in numerical modeling.

Table 2: Material characteristics for the dam-foundation system

Foundation Parameters							
Deformation modulus (GPa)	15	10	08	07	05	04	03
Poisson coefficient	0.2						
Density (Kg/m^3)	2643						
Dam parameters							
Deformation modulus (GPa)	31						
Poisson coefficient	0.2						
Density (Kg/m^3)	2643						
Cracking energy (N/m)	70						

5. MODEL CASE

The Koyna Dam Fig.2 located in southwestern India is one of the most used dams as a reference model. The latter is a concrete gravity dam and is 103m high, 70m base, 14.8m as crest width.
For simplification measures, the width of the valley considered is that of the crest which is 853m. The finite element mesh and the Koyna dam geometry are shown schematically in Fig.2. With equivalent dimensions, other dam profiles are proposed; single curvature arch dam, arch-gravity

profile, and at least double curvature arch dam profile. A comparative analysis of nonlinear seismic behavior while considering the influence of the evolution of the deformation modulus of the rock is carried out.

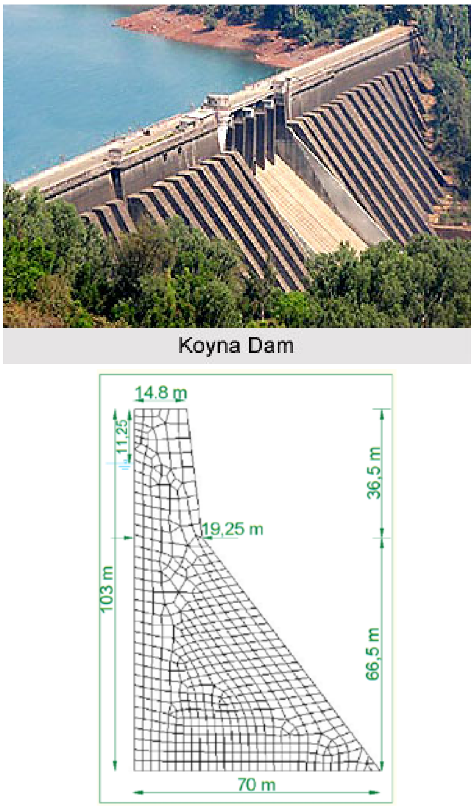

Fig. 2. Geometry and 2D mesh of the Koyna Dam (INDIA)

6. SOLICITATIONS' FEATURES

All profiles analyzed in this study are subject to several types of loading namely,

- Self-weight.
- The hydrostatic pressure of the tank on the upstream face.
- A seismic acceleration presented in Fig.1.
- Trapezoidal pressure acts on the dam-foundation interface.

Drainage and injection efficiency is considered 70% in terms of efficiency.
Fig.3 presents the model of the dam's profiles with different solicitations.

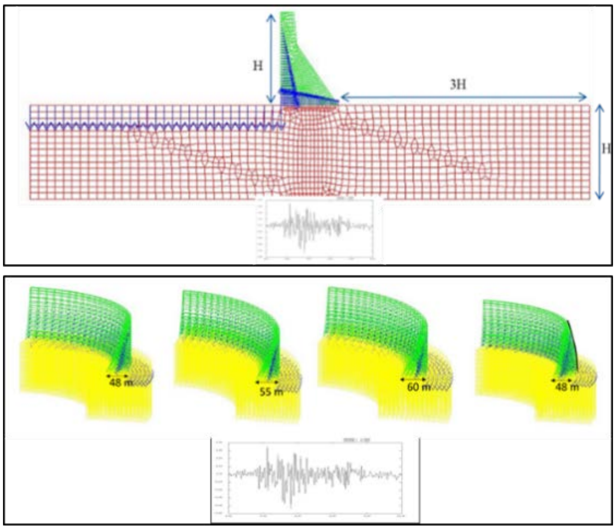

Fig. 3. Meshing and solicitations of the different dam profiles studied.

7. RESULTS OF THE ANALYSIS

7.1 Displacements analysis:

It is crystal clear that earthquakes cause serious disorder in the dams by amplifying the acceleration of the crest. For this, and depending on the variation of the modulus of deformation of rock, a comparative analysis between the profiles of the dams proposed in terms of the displacement of the crest is performed. The maximum crest displacements obtained for each profile are listed in the table below.

Table 3 Maximum displacement of the crest as a function of the variation of the deformation modulus

E (GPa)	15	10	08	07
δ G.D (mm)	19,700	23,960	27,290	30,580
δ S.C.A.D (mm)	0,1975	0,2100	0,2186	0,2268
(**E_b** =48M)				
δ S.C.A.D (mm) (**E_b** =55M)	0,1770	0,1910	0,1773	0,1805
δ A-G.D (mm)	0,1890	0,1716	0,1505	0,1673
δ D.C.A.D (mm)	0,1657	0,2035	0,1950	0,2026

Continued to next page

E (GPa)	05	04	03
δ G.D (mm)	37,780	43,840	58,220
δ S.C.A.D (mm) (**E_b** =48M)	0,2481	0,2606	0,2779
δ S.C.A.D (mm) (**E_b** =55M)	0,1998	0,2099	0,2274
δ A-G.D (mm)	0,1719	0,1947	0,2060
δ D.C.A.D (mm)	0,2279	0,2455	0,2688

Where:
- E: Deformation modulus.
- **δ** G.D: Maximum displacement in the crest of the Gravity Dam.
- **δ**S.C.A.D: Maximum displacement in the crest of the Single Curvature Arch Dam.
- **δ**A-G.D: Maximum displacement in the crest of Arch-Gravity Dam.
- **δ**D.C.A.D: Maximum displacement in the crest of the Double Curvature Arch Dam.

The evolution of the displacement of the crest as a function of the modulus of deformation of the rock is reported in Fig.4, Fig.5, Fig.6, and Fig.7.

The displacement of the crest is inversely proportional to the modulus of deformation for all the cases studied. Nevertheless, the displacements of the gravity dam are very important compared to those of the dams with vaulted form. In addition, the increase of the section of the arch profile reduces displacements by 10 to 20%.

Moreover, it is noted that the double curvature causes a slight reduction in the maximum displacement of the crest.

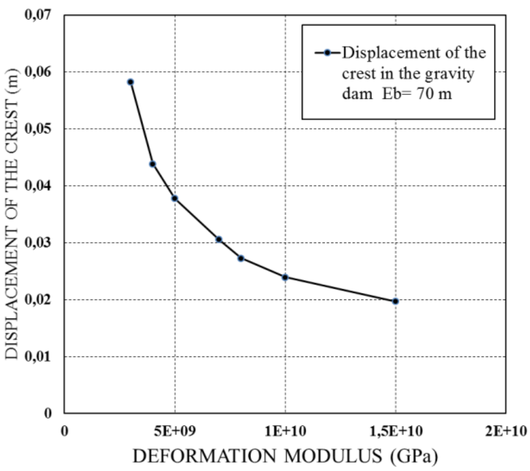

Fig.4 Variation of the displacement of the Crest in the gravity dam according to Deformation modulus

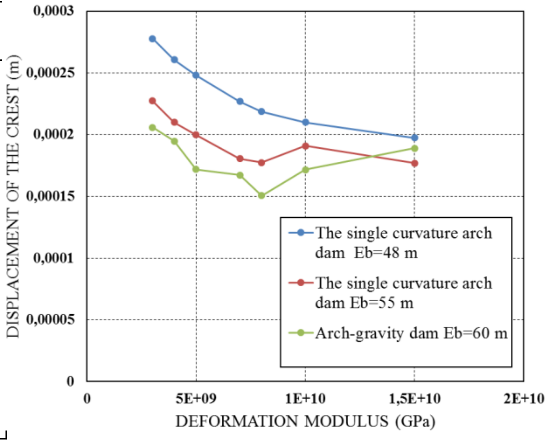

Fig. 5. Variation of the displacement of the crest of single curvature arch dam and the arch-gravity dam according to deformation modulus

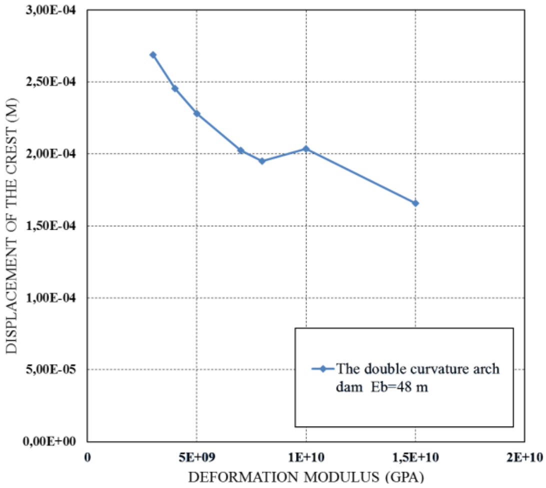

Fig. 6. Variation of the displacement of the crest of the double curvature arch dam with as a function of the deformation modulus

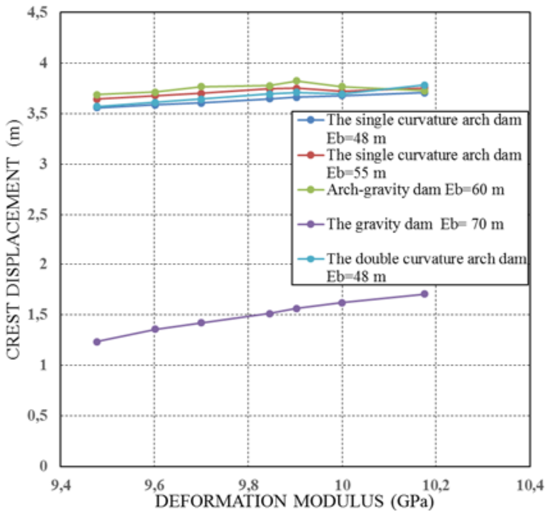

Fig.7 Variations of the displacement logarithm of the crest as a function of the deformation modulus logarithm for the studied cases

7.2 Damage and Crack Analysis

The nonlinear dynamic analysis is performed using a damage model coupled with plasticity. The model has been developed in [14] and energetically regularized in [15] and [16]. The behavior law is described by:

$$\sigma_{ij} = (1-d)\tilde{\sigma}_{ij} = (1-d)C^0_{ijkl}\,\varepsilon_{kl} \qquad (1)$$

The damage evolution is described by an exponential evolution function of the equivalent strain. For the equivalent strain, we use the Mazars's definition.

$$d = 1 - \frac{\varepsilon_{d0}}{\tilde{\varepsilon}_e} exp\left(B\left(\varepsilon_{d0} - \tilde{\varepsilon}_e\right)\right) \qquad (2) \quad (3)$$

$$\tilde{\varepsilon}_e = \sqrt{\left\langle \varepsilon_e^1 \right\rangle^2 + \left\langle \varepsilon_e^2 \right\rangle^2 + \left\langle \varepsilon_e^3 \right\rangle^2} \qquad (4) \quad (5)$$

[16] Gives the fracture energy for mode I of crack propagation

$$\begin{aligned} G_f &= h\int_0^\infty E(1-d)\varepsilon d\varepsilon \\ &= h\int_0^\infty E\left(\frac{\varepsilon_{d0}}{\varepsilon} exp\left[B\left(\varepsilon_{d0} - \varepsilon\right)\right]\right)\varepsilon d\varepsilon \\ &= h\frac{E\varepsilon_{d0}^2}{2} + h\frac{E\varepsilon_{d0}}{B} \end{aligned} \qquad (6)$$

Damage patterns are shown in Figure 8. The gravity dam has a concentration of stresses and location of damage at the dam-foundation interface, unlike the other cases (the single curvature arch dam, the double curvature arch dam, and arch-gravity dam) which remain intact as shown in Fig.8.

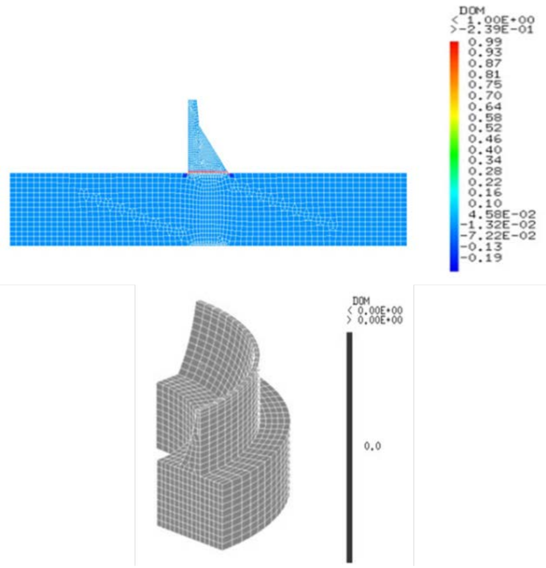

Fig. 8 Damage field for gravity dam and arch dam

For the calculation of crack openings, a practical method for estimating crack opening from a finite element calculation based on damage and/or the plastic model has been developed in [15].

This method is proposed in the Cast3M Finite Elements code (OUVFISS procedure) [17] used in the present study. The method is based on the regularization of the cracking energy.

From a finite element calculation based on a model of nonlinear damage/plasticity, the stress tensor $\boldsymbol{\sigma}$ is obtained using equation (1). The elastic stress is calculated using the total stress:

$$\sigma^e_{ij} = C^0_{ijkl}\varepsilon_{kl} \qquad (7)$$

The total deformation in the solid skeleton $\boldsymbol{\varepsilon}$ is decomposed into two parts: An elastic part $\boldsymbol{\varepsilon^e}$, and a cracking part represented_by the unitary crack opening deformation tensor__(Unitary Crack Opening) $\boldsymbol{\varepsilon^{uco}}$[15].

$$\varepsilon_{ij} = \varepsilon^e_{ij} + \varepsilon^{uco}_{ij} \qquad (8)$$

By multiplying (03) by the undamaged elastic stiffness tensor$\boldsymbol{C^0_{ijkl}}$, we obtain:

$$\begin{aligned} \sigma^e_{ij} &= C^0_{ijkl}\varepsilon_{kl} = C^0_{ijkl}\varepsilon^e_{kl} + C^0_{ijkl}\varepsilon^{uco}_{kl} \\ &= \sigma^s_{ij} + \sigma^{in}_{ij} \end{aligned} \qquad (9)$$

The of crack openings strain tensor is given by:

$$\varepsilon^{uco}_{ij} = (C^0_{ijkl})^{-1}\sigma^{in}_{ij} \qquad (10)$$

The inelastic stress tensor is thus, given by:

$$\sigma^{in}_{ij} = \sigma^e_{ij} - \sigma^s_{ij} \qquad (11)$$

Equation (09) gives the unit crack opening deformation tensor. The value of the normal displacement of the opening of the crack is given by:

$$\delta_n = n_i\delta_{ij}n_j = n_i h\varepsilon^{uco}_{ij}n_j \qquad (12)$$

Where **n** is the unit vector normal to the crack and **h** the width of the finite element where the crack is supposed to appear. The method has been validated under different arbitrary loads and complex boundary conditions [15], [19], [20], [21].

It is shown in Fig.9, the crack-opening field calculated at the end of the loading cycle only for the case of gravity dam because it has a considerable rate of damage.

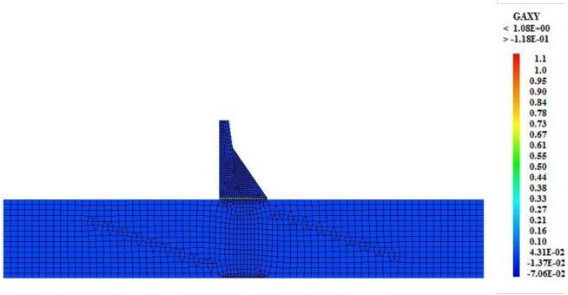

Fig. 9 Crack opening field

Obviously, earthquakes cause a strong amplification of the acceleration at the crest. At the foot of the dam, cracks opening and damage can occur.
In Figure.10, it is clearly demonstrated that the displacement of the crest is proportional to the crack opening at the foot of the gravity dam.

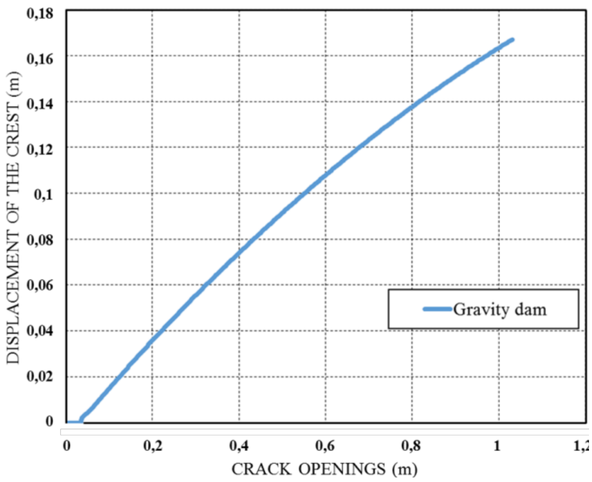

Fig. 10 Variation of displacement of the crest as a function of crack opening at the foot of the gravity-dam

7. CONCLUSION

A nonlinear finite element model of the Koyna (INDIA) dam-foundation system has been developed. This system is treated as two substructures subjected to static and dynamic solicitations whose geology of the site is variable by the change of the modulus of deformation of the rock.
Two profiles of the single curvature arch dam and arch-gravity dam profile of equivalent dimensions were also studied under the same conditions of the gravity dam in order to make a comparison of the dynamic response of the different dam profiles.
Investigations of the effects of taking into account the geology of the site by variation of the deformation modulus on the seismic response of the different dam profiles were undertaken with a view to optimising the profiles in relation to the safety criteria (displacements, damage, and cracking).
The results obtained allow us to conclude the following:
- The displacement of the crest for all the profiles studied is inversely proportional to the modulus of deformation of the rock.
- The displacements of the crest of the arches dams and arch-gravity dams are far reduced compared to those of the gravity dam (a ratio of about 200).
- The double curvature of the dam profile does not have a significant impact on the dynamics characteristics compared to the profile in single curvature.
- The gravity dam is considerably damaged, particularly at the level of the dam-foundation interface contrary to arch profiles (with single and double curvature) or arch-gravity dams, which remains almost without damage.
- The crack opening at the foot of the gravity dam is correlative to the displacement of the crest.
- The parameter deformation modulus of the rock controls, not only the maximum values of the displacements of the crest but also the crack opening triggered during a seismic excitation.
- In seismic regions, and in the case of a rock of poor quality (E ≤4 GPa), it is recommended to think of projecting an arch dam compared to a gravity dam, due to its better vibratory responses in terms of deformation, damage, and cracking, on the one hand, and criteria for optimizing the volume of concrete, on the other hand.
The present work constitutes a first step in exploring the behavior of dams under seismic solicitations. Further investigations taking into account the behavior of dams under coupled solicitation (poromechanics.) are needed to explore new research paths.

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