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UNCERTAINTY QUANTIFICATION OF FRACTURE POTENTIAL AT CONCRETE-ROCK INTERFACE FOR GRAVITY DAMS

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Abstract. The uncertainties are present in engineering projects, in which can be due to materials, models or constructive inaccuracies. This is very important in dams, because the failure of this structure can lead to enormous social, economic and environmental impacts. In addition, dams must resist overtopping occurrence, in which it has intensity, period and duration variabilities. Thus, this paper aims to analyze the behavior of a concrete gravity dam in the presence of a crack along interface dam/foundation, where it is, normally, the weakest zone of the structure. The study of this discontinuity was based in linear elastic fracture mechanics, considering mixed-mode propagation, due to the particulars of the problem. Furthermore, a reliability analysis was made to take account the uncertainty of main design properties and loadings. The results showed the tendency of energy release rate to follow a lognormal distribution. The importance of flood control was evidenced, because the analyzed dam presented high failure probability with overtopping. Moreover, consider triangular uplift or constant uplift acting on the crack generated great differences in reliability analysis.

Keywords: Uncertainty Quantification, Fracture Mechanics, Concrete Gravity Dam

1 Introduction

Dams are big engineering structures which can be designed for storage of water or tailings, energy generation, river regularization, among others and its failure can cause enormous social, economic and environmental impacts. In concrete gravity dams, specially, the failure is associated, especially, to foundation problems, which is the weakest zone of the structure. Thus, if there is a crack along the interface dam/foundation, which can be created due to thermal variations, stress concentrations, among others, its propagation can lead to the structure failure. Furthermore, due to low flood control, these structures are commonly affected by overtopping, as verified by Su [1] in 39,6% of the studied dams in China.

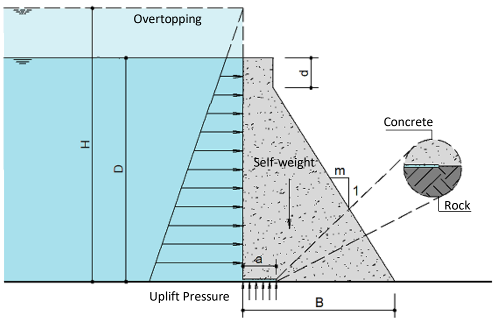
There are in literature some studies about crack propagation along dam/foundation (concrete-rock) interface, as seen in Manfredini *et al.* [2], Bolzon [3] and Barpi and Valente [4]. Furthermore, Plizzari [5] developed geometric equations for mode I and mode II stress intensity factors at the interface. However, the literature lacks the consideration of the uncertainty of the parameters and how this affects the uncertainty in the cracking potential of existing cracks in concrete gravity dams.

The purpose of this paper is to analyze the potential of crack growth along the concrete-rock interface under mixed mode and to quantify the uncertainties of the energy release rate at the interface due to uncertainty of main design properties and loadings.

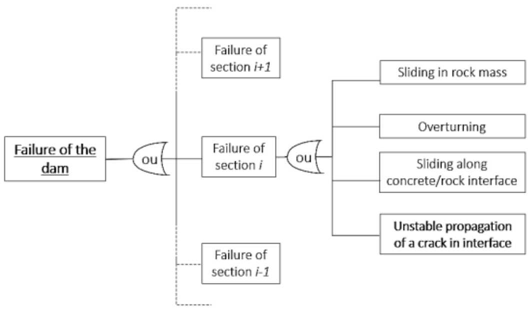
2 Crack propagation along dam/foundation interface

The case study consists on a concrete gravity dam on a rock foundation (Fig. 1a). It was considered the existence of a crack along the interface dam/foundation, which can be formed due to differences in material properties, constructive techniques, thermal variations and stress concentrations. During operation, the crack can propagate unsteadily due to water pressure and lead to the structure failure. The schematization of the problem is exhibited in Fig. 1a, in which the crack is subjected to dam's self-weight, uplift pressure and water pressure due to reservoir. Figure 1b shows the proposed system of failure modes for gravity dams with the highlighted failure mode studied in this paper.

In large structures, as dams, the fracture zone is limited, therefore the LEFM can be well applied [6].



(a)



(b)

Figure 1. Typical concrete dam configuration with overtopping: (a) typical cross section (b) system of failure modes

3 Linear Elastic Fracture Mechanics (LEFM) for interface between materials

The LEFM analyses the materials with global linear elastic behavior and the stress intensity factor (K) characterizes the stress at the crack tip according to three modes of deformation: normal (K_I), in-plane shear (K_{II}) and out-of-plane shear (K_{III}).

Other parameter defined in LEFM is the energy release rate ($\mathcal{G}$), which is a measure of the energy available for an increment of crack extension. If the crack is along an interface between two linear elastic materials, the relation between $\mathcal{G}$ and K is given below [7]:

$$\mathcal{G} = \frac{K^2}{2\cosh^2(\pi\varepsilon)}\left(\frac{1}{\overline{E}_1} + \frac{1}{\overline{E}_2}\right), \tag{1}$$

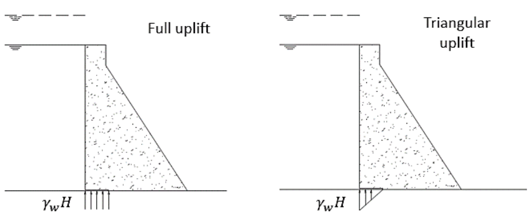
where $\overline{E}_i$ (i=1,2) is the stiffness of each material, which for plane strain state is $E/(1-\nu^2)$, where E is the Young's modulus and ν is Poisson's ratio, and ε is given by:

$$\varepsilon = \frac{1}{2\pi}\ln\left(\frac{\kappa_1 G_2 + G_1}{\kappa_2 G_1 + G_2}\right), \tag{2}$$

where G_i (i=1,2) is the shear modulus of each material and κ_i for plane strain is $3-4\nu_i$.

4 Methodology

In addition to the actions previously mentioned, it was considered two types of uplift pressure, showed in Fig. 2.



(a) (b)

Figure 2. Types of uplift pressure: (a) Full uplift and (b) Triangular uplift

Due to actions and the principle of superposition:

$$K_i = K_i^{sw} + K_i^{fr} + K_i^{ot} + K_i^{ul},$$
$$K_i = \gamma_c D^{(3/2)} d_i^{sw}(\alpha) + \gamma_w D^{(3/2)} d_j^{fr}(\alpha) + \gamma_w (H-D) D^{(1/2)} d_i^{ot}(\alpha) + \gamma_w H D^{(1/2)} d_i^{ul}(\alpha), \tag{3a,b}$$

where the subscript is related to Mode I and Mode II, K_i^{sw} is due to self-weight, K_i^{fr} is related to hydrostatic pressure of full reservoir, K_i^{ot} is due to overtopping pressure and K_i^{ul} is due to uplift pressure along the crack. γ_c and γ_w are the weight densities of concrete and water, the factors H and D are showed in Fig. 1 and $d_i^{\,j}(\alpha)$ were obtained in Plizzari [5].

Table 1 presents the deterministic and random variables used in the simulation.

Table 1. Case study variables

Variable	Mean (μ)	V (σ/μ)	Distribution
Dam height (D)	35, 50 and 80 m	-	-
Downstream slope (m)	0.75[a]	-	-
Dam width (B)	mD	-	-
Water weight density (γ_w)	10 kN/m³	-	-
Concrete Poisson's ratio (ν_c)	0.255[b]	-	-
Rock Poisson's ratio (ν_r)	0.165[b]	-	-
Crack length (a)	0.01-0.23μ_B	0.2	Lognormal
Water level (H)	1.05D	0.1	Extreme Value Type II
Concrete weight density (γ_w)	24 kN/m³	0.04[c]	Normal[c]

Variable	Mean (μ)	V (σ / μ)	Distribution
Elastic modulus of rock (E_{rock})	27.25 GPa[b]	0.25[d]	Lognormal
Elastic modulus of concrete($E_{concrete}$)	33.56 GPa[b]	0.15[c]	Lognormal[c]

[a]: suggested in [5]; [b]: suggested in [8]; [c]: suggested in [9]; [d]: suggested in [1];

In addition to uncertainty quantification, for the reliability analysis, a limit state equation is defined to determine the degree of confidence of the system. In this problem, this equation is given as:

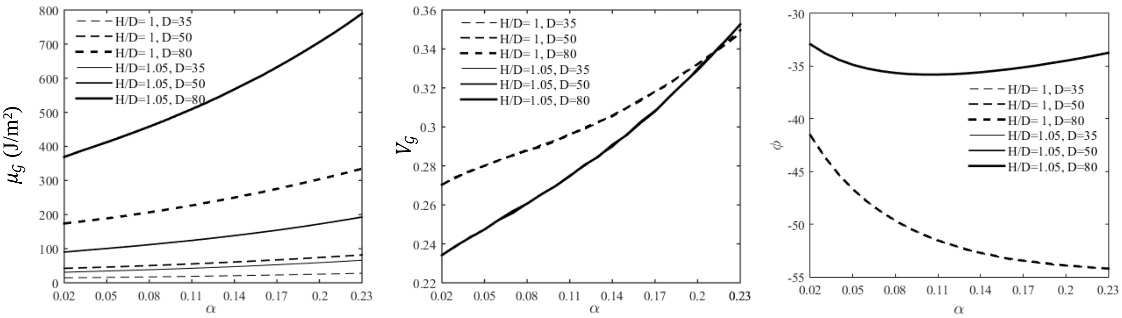
$$\gamma = \mathcal{G}_c - \mathcal{G}, \tag{4}$$

where γ is the performance function and $\mathcal{G}_c$ is the critical energy release rate. The $\mathcal{G}_c$ is calculated with Eq. (1) and the critical stress intensity factor was determined by the regression of experimental data published in Zhong *et al.* [10]. The Monte Carlo Method is used to solve this case by random sample generation and simulation in this proposed model. The failure probability can be determined as the number of times the performance function is less than zero.

5 Results and Discussion

Figure 3a shows the increase of the mean of $\mathcal{G}$ according to the growth of normalized crack length. Despite the increase of $\mathcal{G}$ average with the height increment, the major increase o $\mathcal{G}$ observed is due to occurrence of overtopping. It shows that flood control is fundamental in dam's project. Figure 3b demonstrates the same variation coefficient for different heights only, which is expected due to the change of mean and deviation in same proportion varying the height.

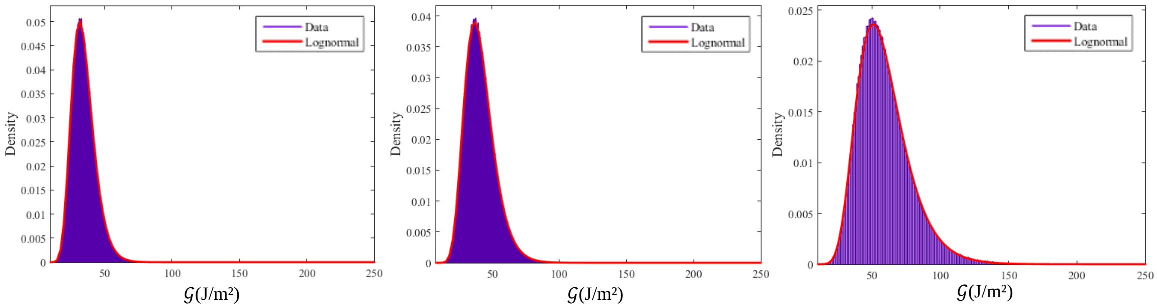
Figure 3c shows the mixity angle behavior considering full uplift. Without occurrence of overtopping, the absolute increase of K_{II} appears to be more accentuated with relation to K_I, what explains the growth of ϕ . With overtopping, from a value of α , K_I becomes more significant than K_{II} and what shows the reduction of ϕ .



(a) (b) (c)

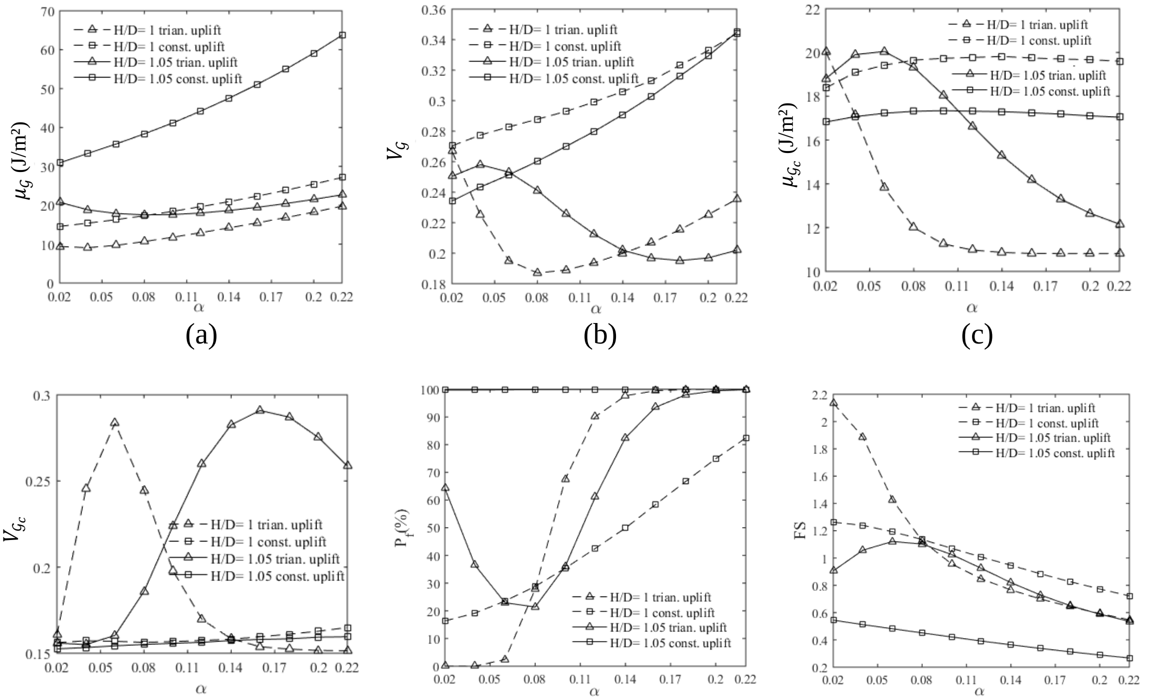
Figure 3. Mixed mode parameters: (a) $\mu_{\mathcal{G}}$, (b) $V_{\mathcal{G}}$ and (c) Mixed mode angle

Figure 4 presents the histograms for $\mathcal{G}$ mixed mode considering the dam's height of 35 m and full uplift. This figure illustrates the increase of the mean and the deviation with normalized crack length seen in Fig. 3. The more open the histogram, greater the deviation. All data fit in a Lognormal distribution. Figure 5a to Fig. 5d exhibit the statistic parameters for $\mathcal{G}$ and $\mathcal{G}_c$, considering *D = 35 m* and two types of uplift pressure. The values of energy release rate for constant uplift is higher than the values for triangular uplift and this form is closer to reality. The variation coefficient for triangular uplift exhibits peaks for values of α near to critical points in the curve of $\mathcal{G}$ and $\mathcal{G}_c$. Figure 5d,e show the failure probability and the security factor. It can be seen for constant uplift and overtopping that the failure will always occur to any α. The probability is acceptable only for triangular uplift and without overtopping, but until α = 0.05.



(a) (b) (c)

Figure 4. Histograms for $\mathcal{G}$ mixed mode, for *D* = 35 m and *H/D* = 1.05: (a) α = 0.05, (b) α = 0.10 and (c) α = 0.20



(a) (b) (c)

(d) (e) (f)

Figure 5. Reliability analysis considering *D* = 35 m and two types of uplift: (a) $\mu_{\mathcal{G}}$, (b) $V_{\mathcal{G}}$, (c) $\mu_{\mathcal{G}_c}$, (d) $V_{\mathcal{G}_c}$, (e) Failure probability and (f) security factor for crack propagation

6 Conclusions

It was showed the non-influence of dam's height in the variation coefficient of energy release rate, which was similarly verified for the mixity angle. Moreover, the data for $\mathcal{G}$ fits in a lognormal distribution, what can be explained due to the majority random variables described as lognormal.

The results evidenced the importance of the flood control to dam's behavior, because the structure presented high failure probability with overtopping. In addition, consider constant uplift can be a more conservative analysis due to the highest values for the parameters and for the failure probability.

The purpose of this paper was reached with the uncertainty quantification of the random variables that describe the case and the confidence determination of the proposed dam.

Acknowledgements

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