Proceedings of the 6th International Conference on Crack Paths (CP2018)

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A compression-shear fracture growing on an arch-gravity dam

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ABSTRACT. In the case of a narrow valley, characterized by a strong rock mass, the excavation can be designed according to the so called convergent way. In this case, the mean value of the compression stresses at the dam-foundation joint increases as the dam moves towards down-stream under the action of the water pressure applied to the up-stream side. During this slip settlement, the stress level in both materials, concrete and rock, remains allowable. It is true that the seismic load is able to increase such a slip displacement, nevertheless, since the structure is designed for horizontal hydrostatic loads, the stress level remains allowable even in such a seismic condition.

The above-mentioned issue was discussed during the 14th Benchmark Workshop on the Numerical Analysis of Dams organized by the International Commission on Large Dams (Stockholm, 6-9 September 2017). The theme B of the above-mentioned Workshop was the static and seismic analysis of the Janneh dam. It is an arc-gravity dam, 157 meters high, now under construction in Lebanon, a high-seismicity region.

The nine participants compared their results, obtained independently from each other and through different numerical models.

In this paper the contribution of the authors is presented and the mechanical hypotheses at the base of the three-dimensional evolution of the crack path, at the dam-foundation joint, is discussed.

KEYWORDS. Non-linear seismic analysis; Contact and friction; arch-gravity dam; interface crack; crack slipping displacement; crack opening displacement.

INTRODUCTION

The Technical Committee A of the International Commission On Large Dam (shortened ICOLD) proposed the Janneh dam (157 m high), under construction in Lebanon, as the subject of the theme B of the 14th International Benchmark Workshop on Numerical Analysis of Dams [1] (see Figure 1). Since the valley is narrow and the strength of the bedrock is high (ultimate compression strength 50 MPa) the dam layout is curved in order to trigger the arch effect, even under normal operating conditions. The arch effect transfers a part of the water pressure to the abutments of the dam laterally. Under seismic load this choice prevents from an unacceptable sliding of the dam on its foundation. Furthermore, the downstream slope of an arch-gravity dam may be steeper than that of a straight gravity dam. As a consequence, less concrete is necessary.

GEOMETRY OF THE DAM

For the purpose of saving concrete and excavation volume, the downstream toe of the dam has been vertically-truncated. Due to this feature, the 2D section of the central block does not satisfy the generally adopted stability criteria for straight gravity dam. The stability of the dam relies consequently on its 3D behaviour. The definition of the upstream and downstream faces of the dam is cylindrical (simple curvature). The main features of the Janneh dam are provided in Table 1.
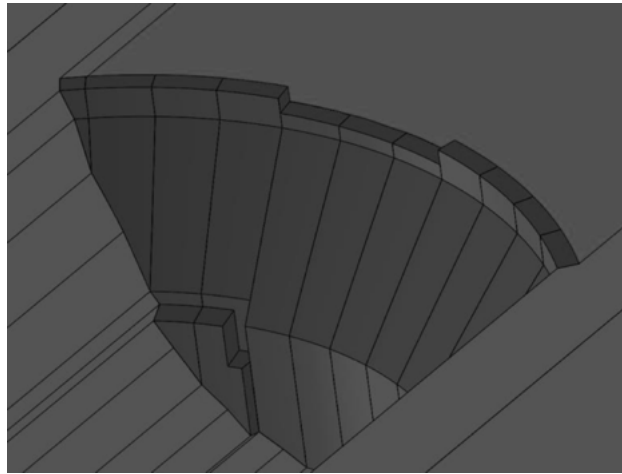
Figure 1: 3D view of Janneh dam (from [1]).

Parameters	Value
Maximum height above excavation	157m
Width at the crest	10 m
Maximum width at the base	66 m approx.
Crest length	300 m approx.
Radius of curvature of the upstream face	240 m
Elevation of the crest	847 m
Elevation of the spillway	839 m
Downstream slope from 831.2m down to 752.4m	0.8H/1V

Table 1: Main features of the Janneh dam (from [1])

Types of analyses

The calculation required to the participants follows a progressive approach: the subsequent stages are of increasing complexity. The concrete and the bedrock always follow a linear elastic constitutive law. The analyses based on a non-linear behaviour of the dam/foundation interface are discussed in this paper. The material properties assumed are shown in Table 2.

Material	Density (kg/m3)	Static deformation modulus (GPa)	Dynamic deformation modulus (GPa)	Poisson's ratio	c (kPa)	ϕ (°)	Tensile strength (MPa)
Concrete	2400	20	30	0.2	-	-	-
Bedrock	2800	25	30	0.25	-	-	-
Water	1000			0.5	-	-	-
Dam / foundation interface	-	-	-	-	0	45	0

Table 2: Material parameters used for the modelling (from [1])

Self-weight calculation

The dam is made of Roller Compacted Concrete (RCC). Therefore, the construction of the dam is simulated by subsequently activating 10 horizontal layers of approximately equivalent thickness. According to the formulation text, the thermal effects and shrinkage are neglected. In the absence of specific creep data for local aggregates and conditions, the ultimate creep coefficient was assumed according to equation A-19 in reference [2] ($\varphi_u = 2.35$). The principle of superposition is assumed to be valid, and the viscoelastic model is based on a Prony series representation [3] of creep date based on reference [4]. Further details on the time dependent model for concrete are presented on [5].

At the end of the self-weight calculation, all the displacements of the model are reset to zero.

Static analysis

The static analyses is carried out for Normal Water Level (shortened NWL) at 839m. The downstream water level is considered at the bedrock level: 690 m. Due to its thickness, the effect of uplift is significant on the dam stability. A drainage efficiency equal to 1/3 is considered 10 m behind the upstream face of the dam. The uplift distribution is shown in Figure 2 and it is assumed as independent on the open region of the dam/foundation interface. The uplift is applied to the dam as external forces.
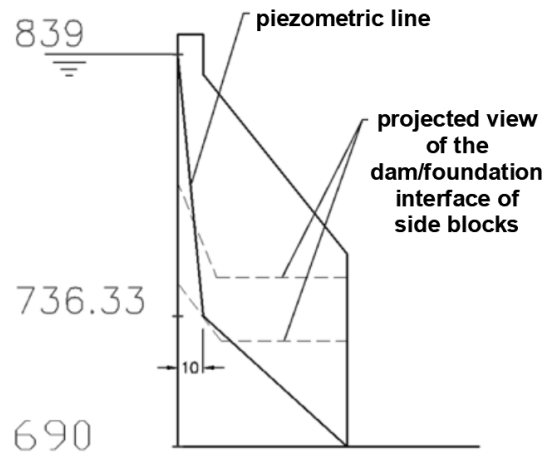

Figure 2: Distribution of uplift across the dam (from [1]).

Seismic analysis

The earthquake response of an arch dam is influenced by its dynamic interaction with foundation rock and the impounded water [6]. The calculations are based on a non-linear model conforming to the previous one, whose results are considered as the initial state. The pseudo-static analysis is carried out considering the following:

- The seismic inertia load is applied toward downstream. A second case, based on inertia load applied toward upstream, is discussed in [5];
- The hydrodynamic pressure is calculated according to Westergaard's approach [7,8];
- The foundation is considered massless;
- The normal water level at 839 m is assumed;

With the above-mentioned hypotheses, the first eigenmode period is 0.39 s (see Figure 3) and its modal mass is equal to 57.8% of the total mass. According to the response spectrum given by the formulators, the related pseudo-acceleration is $6.65\,m/s^2$.
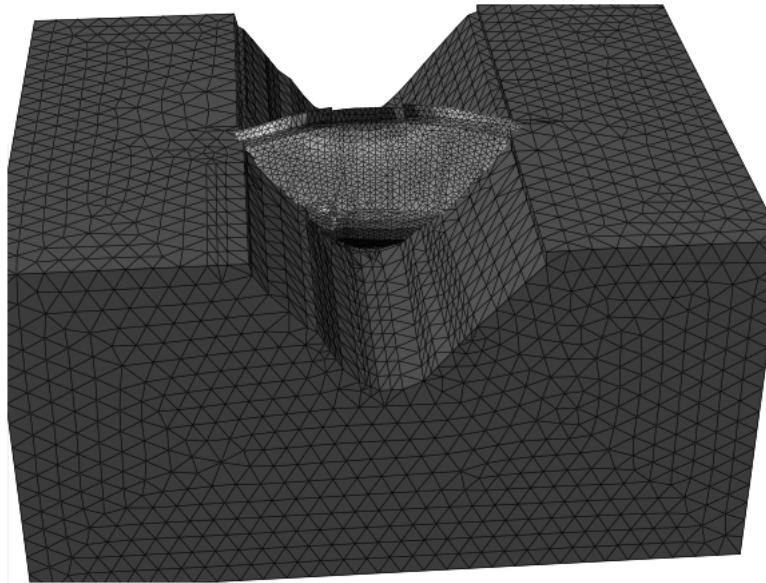
Figure 3: 1st eigenmode of the finite element model used in the numerical simulations (from [5])

Contact formulation

In this paper a node-to-surface contact formulation is used (see [9]). Since the expected maximum value of the sliding displacement is 5 mm and, in the model analysed, the minimum side of the surface triangular elements is 1227 mm, a small sliding formulation is used. In order to enforce the contact constraint, a linear penalty method is used.
When the classic Newton-Raphson method is applied to a contact with friction problem a loss of convergence sometimes occurs [10]. To prevent a large number of sticking-to-slipping transitions, when the slipping displacement is less than 0.2 mm the interface behaviour is assumed as adhesion.

Results

Figure 4 shows the crack opening displacement along the section A-A. The results based on the above-mentioned hypotheses are shown as a black line. The grey lines show the results obtained by the other eight participants to the benchmark. The scattering on the results is mainly due to different approaches to the contact problem with friction. More precisely, some participants use joint elements of finite thickness. Furthermore, in some cases a small value of cohesion is assumed.
Figure 5 shows the real crack tip front line induced by the above-mentioned pseudo-static horizontal forces. The interface points placed upstream of this line are open, the others are closed. With reference to the closed part of the interface, the square size in Figure 6(a) is proportional the ratio τ/σ_n . According to the friction angle shown in Table 2, when this ratio achieves the value 1, a slipping displacement can occur.
Figure 6(b) shows the tensile stresses induced on the rock mass by the seismic load. The maximum local value is 1.812 MPa, allowable for a material characterized by an ultimate compression strength of 50 MPa.

Conclusions

- The above-mentioned approach is able to simulate the growth of a compression-shear crack occurring at the dam-foundation interface.
- The convergent excavation is able to reduce the slipping displacements induced by the pseudo-static actions assumed in the design process.
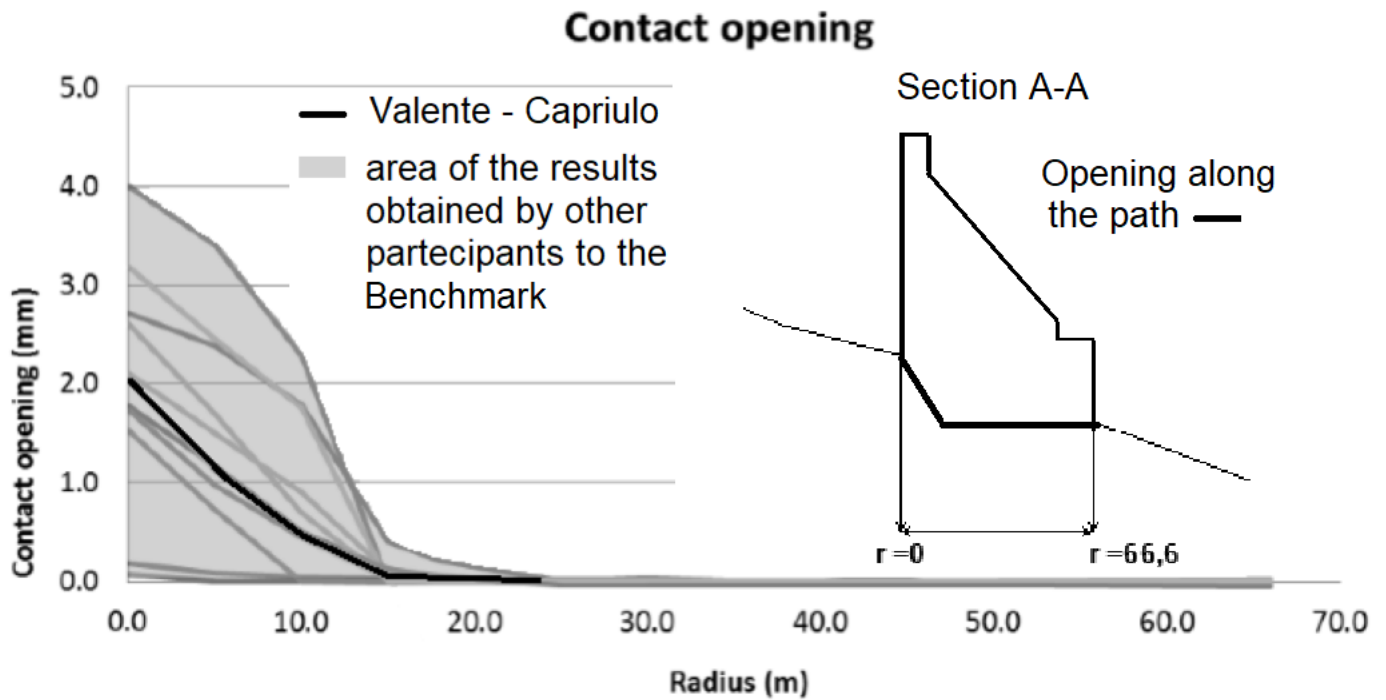- The tensile stresses induced in the rock mass are allowable.

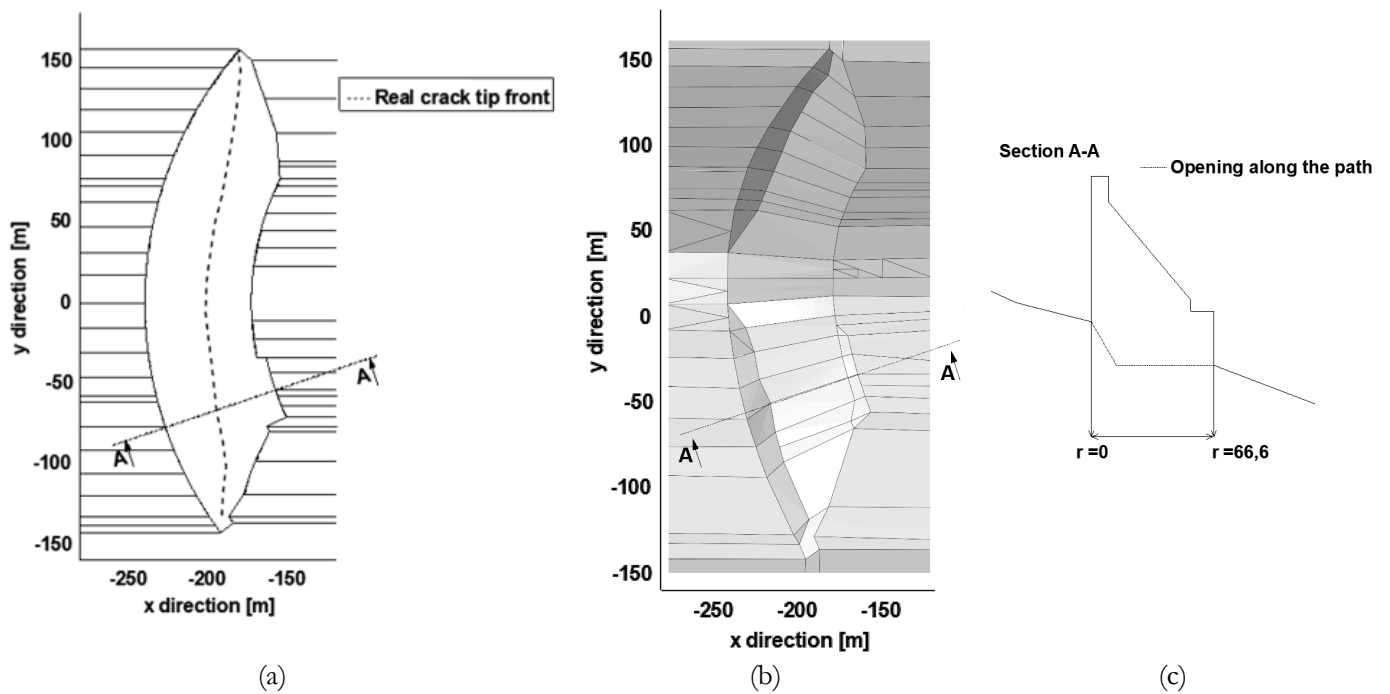Figure 4: Contact opening (mm) at dam/foundation interface (from [1])

Figure 5: (a) Plane view of the dam/foundation interface; (b) Convergent excavation; (c) Dam section.

Acknowledgment

S, Max. Principal
(Avg: 75%)
+1.812e+06
+1.610e+06
+1.407e+06
+1.205e+06
+1.003e+06
+8.012e+05
+5.991e+05
+3.970e+05
+1.949e+05
-7.211e+03
-2.093e+05
-4.114e+05
-6.135e+05

$$\square\ \frac{\tau}{\sigma_n} = 1$$
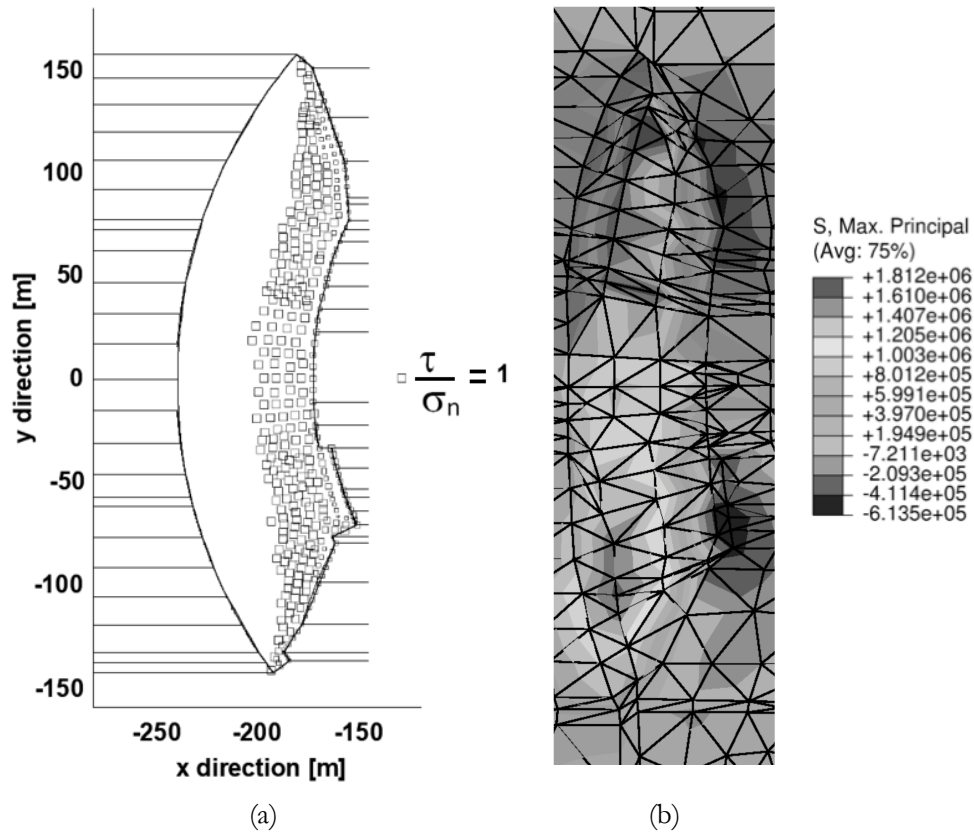
(a)   (b)

Figure 6: (a) tangential stress-pressure ratio; (b) tensile stress in rock mass

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