Sub-critical cohesive crack propagation with hydro-mechanical coupling and friction

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ABSTRACT. Looking at the long-time behaviour of a dam, it is necessary to assume that the water can penetrate a possible crack washing away some components of the concrete. This type of corrosion reduces the tensile strength and fracture energy of the concrete compared to the same parameters measured during a short-time laboratory test. This phenomenon causes the so called sub-critical crack propagation. That is the reason why the International Commission of Large Dams recommends to neglect the tensile strength of the joint between the dam and the foundation, which is the weakest point of a gravity dam.
In these conditions a shear displacement discontinuity starts growing in a point, called Fictitious Crack Tip (shortened FCT),which is still subjected to a compression stress. In order to manage this problem, in this paper the cohesive crack model is re-formulated with the focus on the shear stress component.
In this context, the classical Newton-Raphson method fails to converge to an equilibrium state. Therefore the approach used is based on two stages : (a) a global one in which the FCT is moved ahead of one increment; (b) a local one in which the non-linear conditions occurring in the Fracture Process Zone are taken into account. This two-stage approach, which is known in the literature as a Large Time Increment method, is able to model three different mechanical regimes occurring during the crack propagation between a dam and the foundation rock.

KEYWORDS. Cohesive crack model; Hydro-mechanical coupling; Sub-critical crack propagation; Interface crack; Gravity dam; Contact with friction.

INTRODUCTION

Looking at the long-time behaviour of a dam, it is necessary to assume that the water can penetrate a possible crack washing away some components of the concrete. This type of corrosion reduces the tensile strength and fracture energy of the concrete compared to the same parameters measured during a short-time laboratory test. This phenomenon causes the so called sub-critical crack propagation.
That is the reason why the International Commission of Large Dams [1] (shortened ICOLD) recommends to neglect the tensile strength of the joint between the dam and the foundation, which is the weakest point of a gravity dam. In these conditions a shear displacement discontinuity (Crack Sliding Displacement, shortened CSD) starts growing in a point, called Fictitious Crack Tip (shortened FCT, see Fig.1), which is still subjected to a compression stress. The normal component of the displacement discontinuity (Crack Opening Displacement, shortened COD) will appear later on.

Therefore it is not possible to apply the asymptotic expansion for a cohesive crack [2-4], or other techniques [5-9] . Therefore the cohesive crack model has to be re-formulated with the focus on the shear stress component [10].
In this context, the classical Newton-Raphson method fails to converge to an equilibrium state. Therefore the approach used is based on two stages.

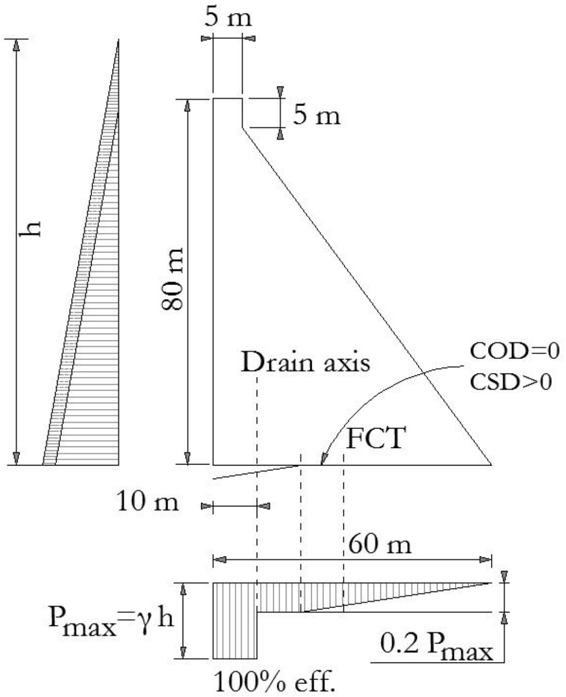

Figure 1: Water pressure distribution and uplift pressure distribution applied to a gravity dam proposed as a benchmark by ICOLD [1]

THE MODEL

One of the main difference between a model related to a specimen tested in the laboratory and a model related to a large structure is due to the effects of the self-weight. The analysis of the gravity dam shown in Fig.1 begins from an initial state, which is a steady-state equilibrium configuration of the dam and of an appropriate portion of the rock foundation. The equilibrium state includes both horizontal and vertical stress components in both materials (concrete and rock). It is important to establish these initial conditions correctly so that the problem begins from an equilibrium state. In this initial state the reservoir is empty , the only load applied is the self-weight and the dam/rock contact is frictionless [11]. Therefore the interface is free from tangential stresses.

Traction-Separation law applied to the Fracture Process Zone

Once the equilibrium state is achieved in this initial phase, following the classical hypothesis of the cohesive crack model , a critical condition at the FCT is looked for. With reference to Fig.1, the points on the right side of the FCT are tied, so that no displacement discontinuity can occur after this operation. With reference to the cohesive crack model, this portion of the interface plays the role of an undamaged ligament. On the contrary, the portion of the interface on the left side of the FCT is called Fracture Process Zone (shortened FPZ). All the non-linear phenomena occurring afterwards are localized into the FPZ. Concrete and rock outside the FPZ behave linearly.
This implementation of the cohesive crack model is based on two stages:
(a) a global one in which the FCT is moved ahead of one increment;
(b) a local one in which the non-linear conditions occurring in the FPZ are taken into account.
This two-stage approach is known in the literature as a Large Time Increment approach [12,13]. The main consequences of this two-stage approach are:
(a)A previous converged load increment is not required.
(b)The iterations done during the local stage are characterized by displacement and stress fields which are not real.

They are just a way to reach a critical condition at FCT and can be forgot. In this case the node-to-segment friction contact problem is solved by means of the Lagrange multipliers[11] Once the critical condition has been reached, it has to be saved and plotted as a step of the global stage, which has a clear physical meaning.
Since the model outside the process zone behaves linearly and includes a crack, a generic load increment occurring during the local stage will induce a singular stress increment at the FCT. The following two assumptions, related to the FPZ, prevent the onset of a singular stress increment at the FCT:
(a) as long as the FPZ is closed, the normal component of the displacement discontinuity vanishes, and therefore the stress intensity factor is $K_1=0$.
In these conditions, following the Coulomb law, the peak value of the tangential stress is :

$$\tau_p = c + \sigma_n \tan(\varphi)$$

(b) Since a new step in the global stages starts only when the FCT is in critical conditions, since a rigid-plastic traction-separation law is assumed (Fig.2), the stress intensity factor remains $K_2=0$ during the iterations of the local stage.

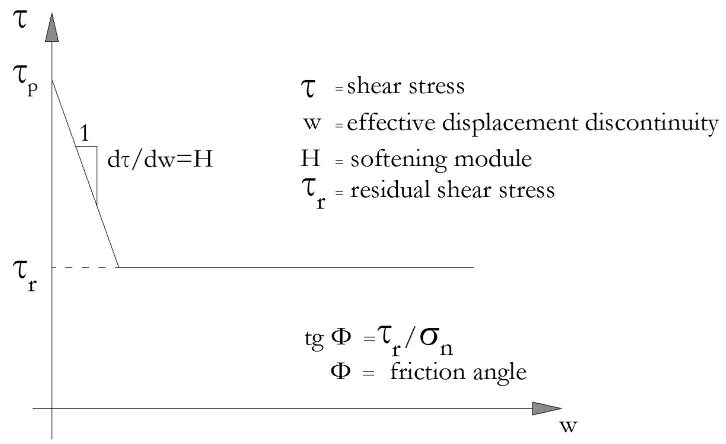

Figure 2: Traction-separation law applied to the Fracture Process Zone.

The effective displacement discontinuity is assumed as:

$$w = (COD^2 + CSD^2)^{1/2}$$

The value assumed for the joint properties c and φ are shown in Table 1. Table 2 shows the material properties.

Parameters	Unit	Value
Peak cohesion c	MPa	0.7
Residual cohesion	MPa	0
Tensile strength	MPa	0
Friction angle φ	deg	30
Softening module H	MPa/mm	-0.7

Table 1: Properties of the rock-concrete interface.

Parameters	Unit	Rock	Concrete
	MPa	41000	24000
Poisson ratio	-	0.10	0.15
Tensile strength	MPa	2.6	1.3

Table 2: Properties of rock and concrete.

Crack growth conditions in the closeness of the Fictitious Crack Tip

The above mentioned hypotheses are related to a surface : the dam-to-foundation interface. On the contrary, the following hypotheses are related to a volume of dam concrete and a volume of rock foundation..

Both domain are meshed by means of triangular elements of constant strain type. As shown in Fig.3, the dam is divided into 2205 elements and the foundation into 5673 elements. In the closeness of the interface, the triangles are assumed as equilateral, with a side of 0.6 m. The four stress components are computed in two elements connected to the joint and to the FCT: one for the dam and another for the foundation. The stress level is compared to the Mohr-Coulomb criterion shown in Fig.4.

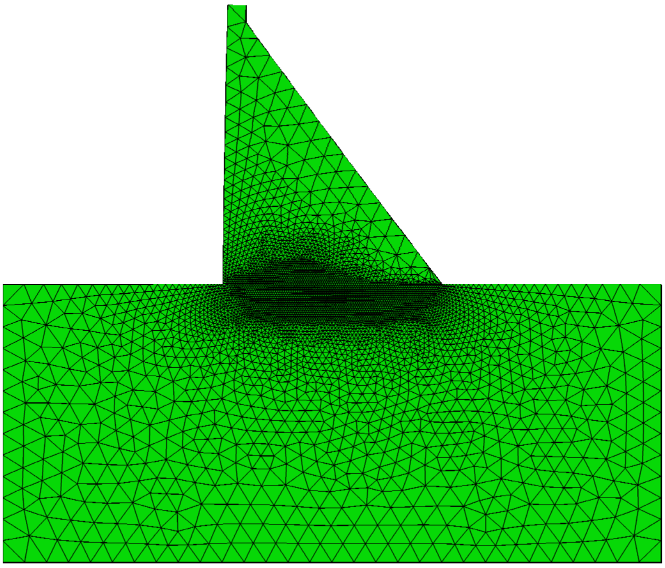

Figure 3: Finite element mesh used in the numerical analysis

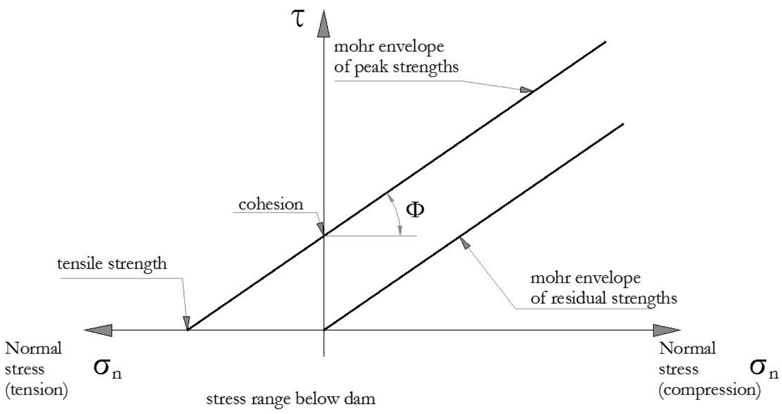

Figure 4: Mohr-Coulomb criterion applied at the Fictitious Crack Tip.

The hydro-mechanical coupling hypothesis

Fig.1 shows the assumed distribution of uplift pressure in the case of complete drain efficiency.
The pressure is assumed constant up to the point where the crack opening displacement is larger than a threshold value of 1.e-6 m. Elsewhere the pressure is a linear function of the position, vanishing at the downstream edge.

RESULTS

Fig. 5 show the results at the end of the local stage when the distance of the FCT from the upstream edge is 7.2 m. The circular symbol shows the crack opening displacement (shortened COD). Similarly, the square symbol shows the crack sliding displacement (shortened CSD). The rhomb symbol shows the contact pressures and the triangular symbol shows the tangential stresses. Both stress components are divided by 1 MPa.
Similarly, Figs.6,7,8,9 and 10 refer to a distance respectively of 12,18,24,30 and 36 m.
It is possible to observe that the method is able to manage three different regimes: (a) in Fig. 5 the FPZ is not completely developed, (b) in Figg. 6,7,8,9 the point where the tangential cohesive stress vanishes is open (COD > 0), (c) in Figg.10 the point where the tangential cohesive stress vanishes is closed (pressure >0).

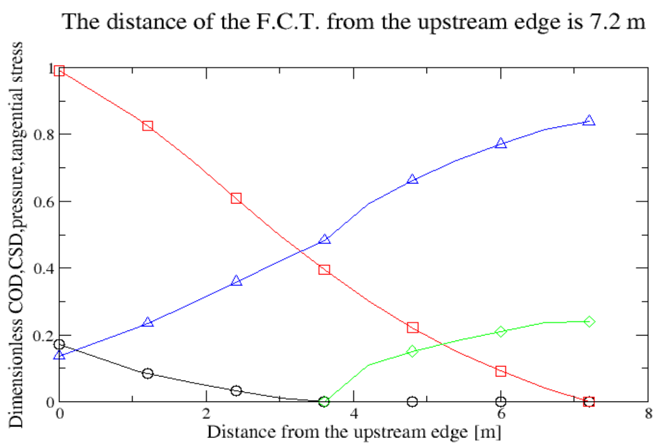

Figure 5: Results for the first step of the global stage. COD and CSD are divided by 0.8 mm. The load level is 70% of full reservoir.

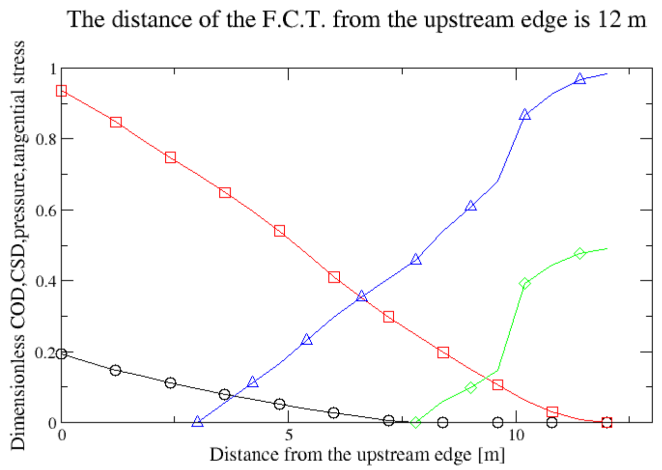

Figure 6: Results for the second step of the global stage. COD and CSD are divided by 1.4 mm The load level is 80% of full reservoir.

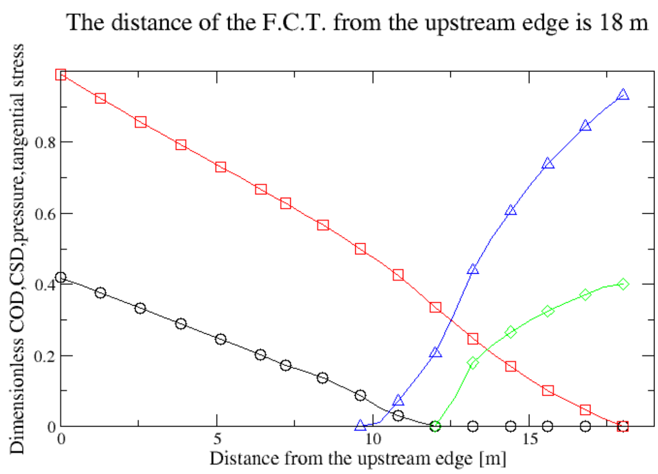

Figure 7: Results for the third step of the global stage. COD and CSD are divided by 2.1 mm. The load level is 94.96 % of full reservoir.

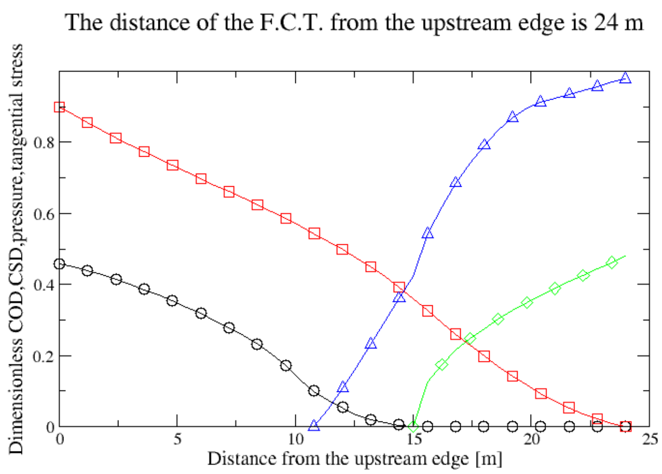

Figure 8: Results for the 4-th step of the global stage . COD and CSD are divided by 2.7 mm. The water level is 0.28 m above the dam crest.

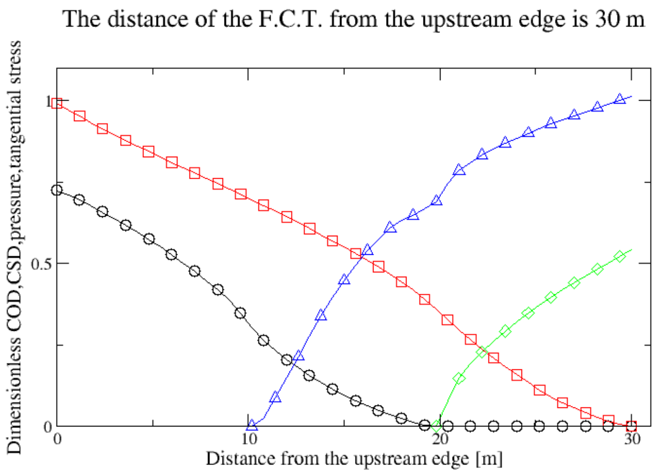

Figure 9: Results for the 5-th step of the global stage . COD and CSD are divided by 3.0 mm. The water level is 0.5 m above the dam crest.

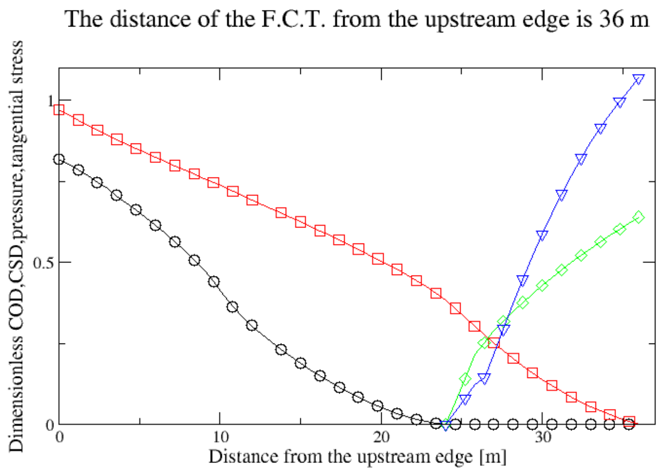

Figure 10: Results for the 6-th step of the global stage . COD and CSD are divided by 3.7 mm. The water level is 0.8 m above the dam crest.

CONCLUSIONS

1) The cohesive crack model can be used in the context of a large-scale engineering problem.
2) The uplift pressure induced by the water penetrating the open part of the crack can be taken into account.
3) The corrosion induced by the water penetrating the closed part of the crack can be taken into account through an appropriate reduction of the joint strength properties (sub-critical crack propagation).
4) In this case the phenomenon cannot be modeled through a continuous sequence of load increment in the context of the Newton-Raphson method. On the contrary, it is necessary to divide the whole process in a sequence of LArge Time INcrement (shortened LATIN). Therefore each large time increment can be simulated independently from the previous one.
5) This two-stage approach is able to model three different mechanical regimes occurring during the crack propagation process.

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