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# FDM-DEM modelling of a rockfill dam with dry-stone pitching: a case study

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**ABSTRACT:** Rockfill dams with dry-stone pitching are hydraulic structures mainly built in the early 20th century. Their upstream and downstream faces are protected by stones laid by hand without mortar. Electricity of France, a French stakeholder, currently operates about ten dams of this kind in France. However, the mechanical behaviour of such dams is not yet well understood, and few studies have been conducted to quantify their seismic and static behaviour and resistance. This study includes the modelling of one of those dams located in the French Pyrenees mountains. It is carried out using the mixed continuum-discrete numerical approach validated in a prior work. The dam body is modelled as a continuum medium and the pitching dry stones as discrete bodies. First, the construction phases and reservoir filling processes are modelled. The obtained displacements are analysed and compared with those observed on-site to validate the model parameters. Then, the dam seismic resistance is evaluated by performing pseudo-static tests provided by tilting the dam until failure. The static and seismic safety factors are calculated accordingly and the role of the pitching in the dam resistance is specified.

**Keywords:** dam; stone; DEM; FDM; rockfill

## 1 INTRODUCTION

Rockfill dams with dry-stone pitching have been part of the French heritage for hundreds of years. They consist of an embankment made of decametric blocks, framed on both its upstream and downstream sides by a protective pitching made of hand-arranged stones without mortar.

Thirteen dams of this type were built in France between 1940 and 1960: the company “Électricité de France” (EDF) still operates most of them. Nevertheless, the mechanical behaviour of such a structure, which is discrete in nature and can withstand large deformations, is not understood in detail: only few academic studies have been conducted to investigate their mechanical behaviour and quantify their resistance to both static and seismic loads. Following the completion of PEDRA research project (2011-2014) dedicated to the design of dry-stone masonry structures and funded by the French Ministry of Ecological Transition, EDF funded an experimental campaign about rockfill dams with a dry-stone pitching. Thus, four scaled-down physical models (about 1/10th) of rockfill dams with dry-stone pitching were built. The physical models were then subjected to a global rotation until failure: throughout the tilting process, the displacement of the downstream pitching was monitored using six sensors as well as cameras.

These experiments were successfully simulated using a mixed continuum-discrete approach (FDM-DEM) where the dam body was modelled by a continuum approach while the blocks of the dry-stone pitching were modelled as interacting individual bodies (Haidar et al., 2022, 2023). More precisely, in this preliminary work, an elastoplastic model (LK-Enroch) developed by EDF was used to describe the mechanical behaviour of the dam body made of rockfill. The stones forming the pitching, assumed to be rigid and with deformable contacts, were modelled in a discrete manner (DEM). The advantage of using DEM is to make it possible to consider the block shape and degraded contact properties between blocks on the overall resistance of the dam. The numerical model gave a good prediction of the dam strength (tilting angles at failure) and the downstream pitching displacements throughout the tilting process in the four modelled configurations.

On the basis of this past work, this study presents the modelling of one of the rockfill dams with a dry-stone pitching located in the Pyrenees mountains (France). The objective is to study the static resistance of the dam and its resistance against seismic loading throughout a simplified pseudo-static approach. Safety factors will quantify this resistance including after construction and filling with water. *FLAC3D* software was used to model the dam body while the stones of the pitching were modelled as individual elements using *PFC3D* software.

## 2 DESCRIPTION OF ESCOUBOUS DAM

The rockfill dam with drystone pitching studied in this section (Figure 1) is called Escoubous and was built between 1951 and 1953. Its height is of 16 m on the upstream side and 18 m on the downstream side. The downstream side has a slope of 1H/1V while the upstream slope varies from 1H/1V at the base of the dam to 0.8H/1V near the crest. It has a crest of 2 m width and a berm of 1.2 m width at mid-height of the downstream face. The rockfill that constitutes the dam body was progressively dumped during construction without compaction, and thus corresponds to a loose state. The porosity $n$ of the dam body was estimated at 0.45, $D_{50}$ to be 15 cm with a uniformity coefficient smaller than 3. The pitching is made of 30 cm thick parallelepiped granite blocks. The rockfill located on the dam body faces were arranged in a denser state to facilitate the installation of the dry-stone pitching. This dense layer is 20 cm thick on the upstream side and 90 cm thick on the downstream side.

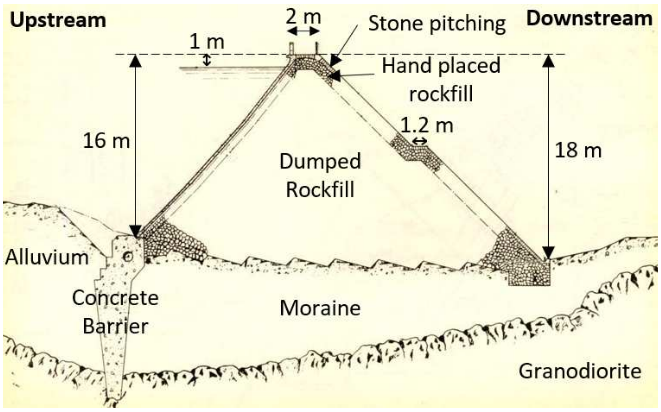


*Figure 1. Historical section of Escoubous dam*

## 3 HISTORICAL DATA

There is almost no historical data related to the tracking of the dam deformations during its construction and impoundment in 1954. However, early measurements (1955-1959 period when the reservoir elevation rose to 2040 m corresponding to 15 m of water level) indicated a maximum downstream displacement of 50 mm during this process.

By extrapolation of the theory established on structures of this type (Gréziolles dam in particular, which is operated by EDF and has been much more auscultated), we should expect at the dam crest during the first impoundment:

- settlements of 0.7% of the dam, i.e. 11.2-12.6 cm;
- a horizontal downstream displacement of 0.35% of the dam height, i.e. 5.6-6.4 cm.

Plots E, F, G and H in Figure 2 show the displacement evolution at 4 points at the dam crest as a function of the years after construction. The central points, F and G, are the highest and relatively similar in cross section. Since the in-situ measurements were only available between 1983 and 2008, the reconstruction of the displacement profile at these points has been extrapolated in the years before 1983 and after 2008 by EDF (Figure 2). The orders of magnitude of the settlements in the early years (first years of service of the structure after impoundment) were then estimated to have been about 10 cm in the late 1950s (Figure 2).

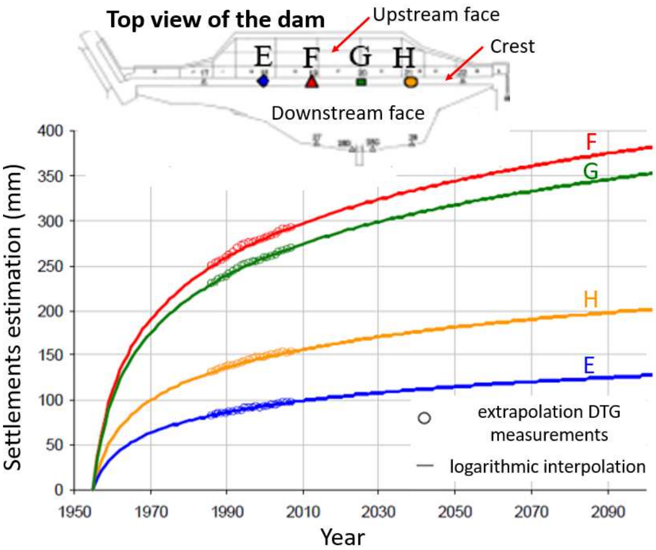


*Figure 2. Reconstruction (logarithmic evolution) of crest settlements by EDF from measurements made between 1983 and 2008*

## 4 NUMERICAL MODEL

### 4.1 *Model geometry and boundary conditions*

The dam consists of the rockfill forming its body, a layer of hand-placed rockfill and the dry-stone pitching (Figure 3). The dam rests on a moraine foundation with a granodiorite mass underneath and on the downstream part of the foundation. The upstream part of the foundation consists of alluvium deposits and a concrete barrier was placed on the upstream toe of the dam. The 20 cm thick concrete upstream mask was not modelled explicitly. It was integrated with the upstream pitching by increasing its weight and adding bonds between its blocks, compatible with the tensile resistance of concrete material.

The width of the model is 9 m, and the lateral number of blocks is approximately 22. This width was calibrated to ensure that the dam behaviour is not highly influenced by the lateral boundary conditions. The pitching blocks have the following dimensions: 20×30×40 $cm^3$ (height × thickness × width). The number of elements in the model is 120,960 and the number of blocks forming the pitching is 5,613. The slope is streamlined and taken as 1H/1V on both sides of the dam. The dam is 16 m high on the upstream side and 18 m high on the downstream side. More details about the geometry of the system are given in Figure 3.

The dam body mesh size was chosen to have enough grid points in contact with the pitching blocks (namely at least one contact point)

Concerning the boundary conditions, the two lateral sides of the model (gridpoints and pitching blocks) are fixed in the direction normal to the boundary and free to move in the other directions. The vertical sides of the foundation are fixed in the horizontal direction, free to move on the other directions. The base of the foundation is fixed in the vertical direction and its gridpoints are free to move in the other directions. As for the pitching, the first row of stones is totally fixed on both sides of the dam.

## *4.2 Model parameters*

### *4.2.1 Dam body: Rockfill*

The dam body, which is formed of dumped rockfill, was modelled using the LK-Enroch model. Detailed description of this model can be found in Chen (2012). The model parameters are listed in Table 1. These parameters were extrapolated from a previous study conducted by EDF on a similar rockfill dam (Silvestre, 2010). This latter dam has been the subject of more information and experimental tests that allowed the calibration of the parameters of the numerical model.

*Table 1. LKE model parameters of the dam body*

| **E** | **$\upsilon$** | **$n_{elas}$** | **$\sigma_c$** | **$a_0$** | **$m_0$** |
|---|---|---|---|---|---|
| 75 MPa | 0.25 | 0.55 | 135 MPa | 1 | 0.01 |
| **$a_{peak}$** | **$m_{peak}$** | **$\dot{\gamma}_{peak}$** | **$\dot{\gamma}_{res}$** | **$X_{ams}$** | **$\eta$** |
| 0.9 | 2.2 | 0.1 | 0.6 | 0.005 | 10 |
| **$\Phi_{res}$** | **$\Psi_0$** | **$p_{c0}$** | **$\beta$** | | |
| 33° | 50° | 60 kPa | 20 | | |

### *4.2.2 Hand-placed rockfill layer*

The denser superficial rockfill layer on the two faces of the dam under the pitching was modelled using the typical elastic perfectly plastic Mohr-Coulomb (MC) model. Its parameters (Table 2) were chosen from the literature. The porosity of this hand-laid layer was estimated to be about 0.2 (Vincens et al., 2016). The friction angle was chosen equal to 58° using the diagram of Leps (1970) and considering a dense material with low confining pressure. The dilatancy angle was estimated equal to 18° using Bolton's approach (Bolton, 1986). The Poisson's ratio was taken equal to 0.25 and the cohesion to 0.

Since the porosity of the backfill was estimated to be equal to 0.45 with contrast with the porosity of the hand-placed rockfill layer of 0.2 (Vincens et al., 2016), the Young's modulus of this latter was taken about 11 times the value of the dumped rockfill of the dam body. This choice was made according to a study mentioned in Vincens (2016).

*Table 2. Model parameters of the hand-placed denser superficial rockfill layer*

| **E** | **$\upsilon$** | **$\phi$** | **$\Psi$** | **C** |
|---|---|---|---|---|
| 75 × 11 MPa | 0.25 | 58° | 18° | 0 |

### *4.2.3 Foundation*

The different parts of the foundation, including the granodiorite, the alluvium deposit, the concrete barrier, and the moraine, are modelled using Mohr-Coulomb model. The model parameters for these different sub-systems were deduced from previous studies in accordance with their characteristics (Alejano and Alonso, 2005; Bourdeau, 1997; Davre and Giraud, 1986; Hubbard et al., 2005; Laloui et al., 2006).

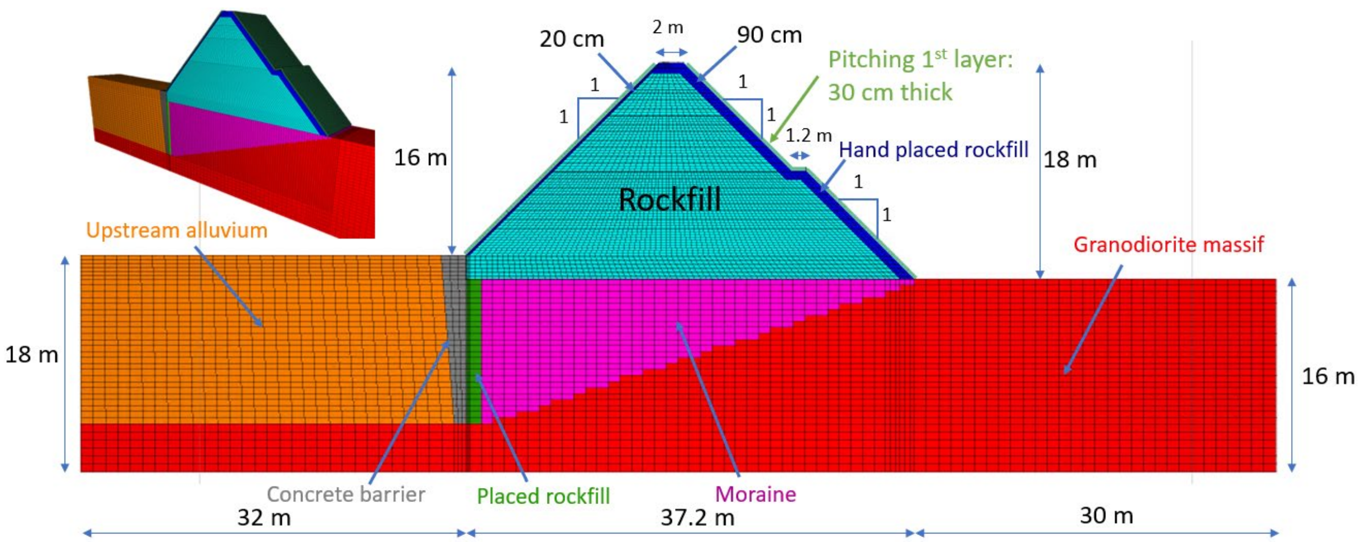


*Figure 3. Coupled FLAC3D-PFC3D numerical model of the studied dam and its different elements and their dimensions*

### 4.2.4 *Dry-stone pitching*

A linear frictional contact law is used for the deformable contacts between the pitching blocks. A block-block contact friction coefficient μ= 0.7 is used for the pitching blocks (Alejano et al., 2012). The effective modulus $E^*$ was found to be equal to 50 MPa and the stiffness ratio $K^*$ equal to 2. A typical overall damping of 0.7 is used for static computations (Cundall and Strack, 1979).

The 20 cm wide upstream concrete mask was considered in our model by increasing the weight of the upstream blocks and adding bonds between them with a tensile strength of 3.9 MPa and a cohesion of 3 MPa. These values, taken from the literature, are average concrete values obtained from experiments on concrete specimens (Lelovic and Vasovic, 2020).

The coupling between the *PFC3D* and *FLAC3D* software is activated throughout the pitching-backfill interface. A purely frictional linear elastic model, using the same set of parameters as the one set for the contact between blocks, is used to simulate the interface mechanical behaviour which is consistent with the characteristics of the contact between the dam body and the pitching.

## 4.3 *Construction and water filling: model validation*

The dam construction was modelled throughout four stages to mimic in a simplified way the true progressive rising of the structure. Figure 4 and Figure 5 give the horizontal and vertical displacement fields obtained at the end of construction. The final settlement at the crest was found close to 30 cm.

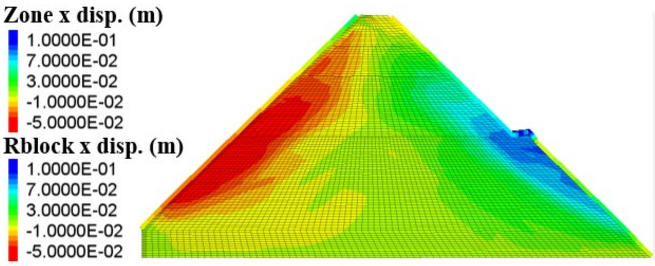


*Figure 4. Horizontal displacements of the dam after construction*

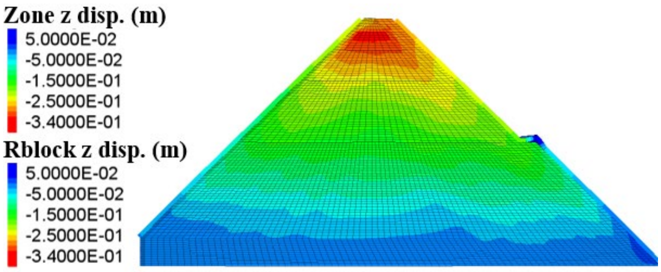


*Figure 5. Vertical displacements of the dam after construction*

After construction, the water filling of the dam reservoir was modelled by gradually increasing the water level until the maximum level (15 m above the upstream foundation). The water level was simulated by applying normal forces on the faces of the upstream pitching blocks, knowing the force on each block depends on its depth below the water level. The distribution of forces applied to the upstream blocks at the end of the water filling process is shown in Figure 6. Since the upstream face of the dam was considered as impermeable due to the upstream mask, no water flow into the dam body was simulated neither the existence of pore pressure.

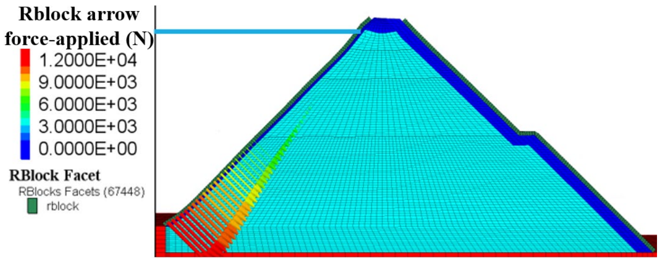


*Figure 6. Forces applied on the upstream pitching stones during reservoir water filling*

The horizontal and vertical displacements at the end of the water filling of the reservoir are given in Figure 7 and Figure 8, respectively. The water pressure leads to displacements in the whole body of the dam which affects the downstream part of the dam.

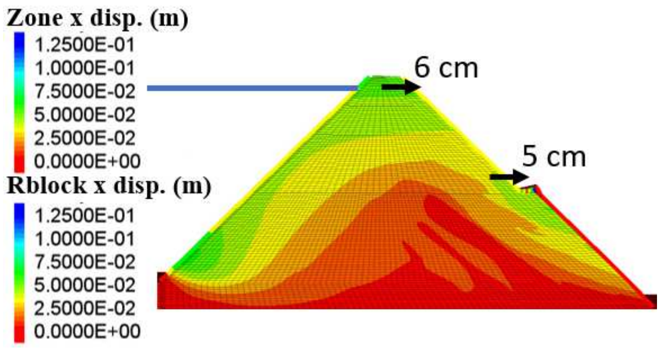


*Figure 7. Horizontal displacements of the dam after water filling*

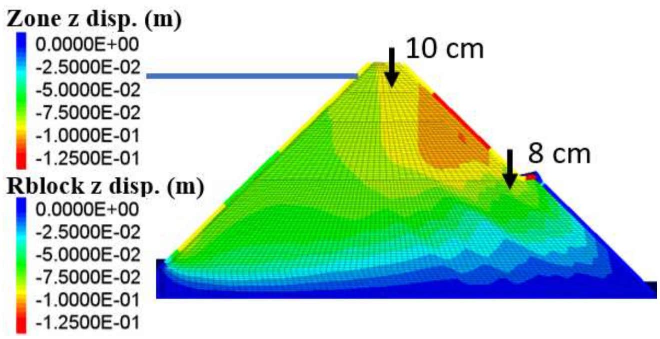


*Figure 8. Vertical displacements of the dam after water filling*

The horizontal and vertical displacements at the crest are 6 cm and 10 cm, respectively, which are very close to the extrapolated historical values described in Section

3: this validates the overall model and the involved model parameters.

### 4.4 Dam safety factor assessment

Two approaches are used to assess the dam safety factors. The first approach allows us to estimate the safety towards a static failure obtained by reducing the mechanical properties of the whole dam. The second approach is related to the estimate of the safety against a seismic loading determined throughout a simplified technique denoted pseudo-static method which consists of tilting the whole system towards failure.

#### 4.4.1 Static safety factor

According to this approach, the mechanical parameters related to the shear resistance of the materials were reduced gradually by increasing the safety factor $F_\phi$ until failure is detected. A failure criterion based on the unbalanced forces ratio and the pitching kinetic energy was developed and used to detect the failure of the system.

Regarding the dam body, both compressive strength $\sigma_c$ and residual friction angle $\varphi_{res}$ parameters, are reduced in this approach using equation (1) and equation (2). $a_{peak}$ is a parameter of LK-Enroch model (Table 1).

$$\sigma_c = \frac{\sigma_{c-max}}{F_\phi^{\,1/(1-a_{peak})}} \quad (1)$$

$$\tan\varphi_{res} = \frac{\tan\varphi_{res-max}}{F_\phi} \quad (2)$$

In parallel, the stone pitching strength is also degraded by reducing the block-block contact friction angle using equation (3).

$$\tan\varphi_P = \frac{\tan\varphi_{P\ initial}}{F_\phi} \quad (3)$$

The safety factor obtained using this approach is $F_\phi$=1.4. The evaluation of this factor by considering the presence of water pressure (reservoir filled) leads to the same value. Indeed, failure is generally triggered in the upper third of the dam where the hydrostatic pressure on the upstream face is relatively low.

#### 4.4.2 Pseudo-static safety factor

Pseudo-static safety factor $F_\theta$ is related to the effect of horizontal inertial forces on the system generated throughout the tilting of the model. It is defined by Equation (4) where $\boldsymbol{\alpha}$ is the slope of the dam face (equal to 45 °) and $\theta_{Failure}$ is the tilting angle at failure.

$$F_\theta = \frac{\tan(\alpha + \theta_{failure})}{\tan(\alpha)} \quad (4)$$

The whole system was tilted after the end of the construction process (without water reservoir) until reaching failure. The physical rotation was simulated by the rotation of the gravity vector. The dam failed at a rotation angle of 8° which gives a safety factor of 1.33 using equation (4).

### 4.5 Dry-stone pitching stability role

To quantify the role played by the dry-stone pitching in the stability of the dam, the dam was modelled without the 2 faces of dry-stone pitching.

In such a case, the dam failed at the last stage of construction (Figure 9). A failure surface was developed from the crest to the bottom of the upstream face. This failure is provoked by the loss of the added resistance due to the pitching stones. The failure developed on the upstream side since the hand-placed layer is thinner on this side (20 cm) compared to the downstream side (90 cm thick).

In conclusion, the dam is not stable without the dry-stone pitching with a factor of safety of less than 1. This failure was expected since the backfill is characterised by an internal friction angle of about 42° which is smaller than the slope angle of the dam (45°).

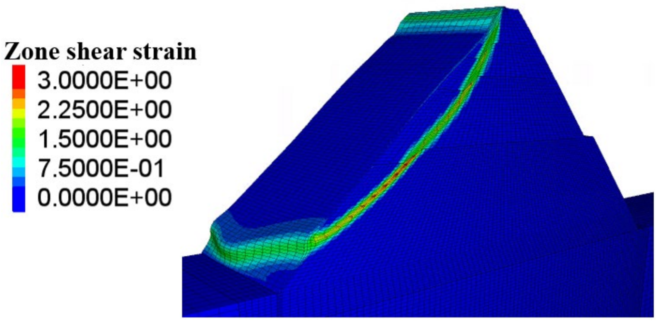


*Figure 9. Failure during the dam construction, without the dry-stone pitching but with the hand-placed layers*

## 5 CONCLUSIONS

A rockfill dam with dry-stone pitching, located in the Pyrenees mountains in France and built in the early 1950s, was studied using a mixed FDM-DEM numerical approach. This approach was already validated in a previous study on similar structures.

The dam was first constructed in several stages and then the water reservoir was filled. The set of model parameters was definitively validated by comparing the simulated horizontal and vertical displacements after water filling with the expected ones taken from reconstructed historical data.

The safety of the dam was assessed using two approaches, one related to the static safety margin and the second one to an equivalent seismic safety margin. The obtained safety factors are in the order of 1.3-1.4.

Finally, the key role of the dry-stone pitching in the dam stability is emphasized since, without it, failure was obtained before the completion of the dam body.

## 6 ACKNOWLEDGEMENTS

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