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From Scaled-Down to Full-Scale Rockfill Dams with Dry-Stone Pitching: A Numerical Study

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Abstract **-** Rockfill dams with dry-stone pitching are about one hundred years old structures that are present in the French heritage. They are composed of a backfill made of decametric blocks and a protective pitching made of hand-placed stones without mortar on both dam's downstream and upstream faces. Electricity of France, a French stakeholder, operates approximately ten dams of this kind. However, the mechanical behavior of such a structure which is discrete in nature and that can bear large deformations is not very well understood, even if few studies have been conducted over the last decades. This study is a step forward for a better understanding of the role of the pitching in both static and seismic behaviors of such dams. Firstly, a mixed DEM-FEM numerical approach for the modeling of such dams is developed and validated based on experiments involving scaled-down rockfill dams. Secondly, simulations on full-scale dams are carried out and the role of the pitching considering different building techniques or properties is quantified. They clearly show large-scale effects at stake in the structure and the key role of the pitching weight and pitching-backfill interface. Finally, the perturbation in the dam resistance induced by a berm which is typically built on the downstream face is investigated.

Keywords**:** dam, DEM, FEM, scale effect, berm, stone

1. Introduction

There exists around the world a vast heritage of civil engineering structures built with the dry-stone technique. This ancient method of construction consists in arranging rubble stones without mortar in a certain pattern. In addition to the extensive history of dry-stone walls used to maintain slopes, dams have also been constructed using this method. For instance, 13 rockfill dams with a dry-stone pitching on the upstream and downstream faces were constructed in France between 1940 and 1960. The stakeholder Electricity of France (EDF) continues to operate most of them.

To better understand the behavior of such structures against earthquakes and to provide a database for additional numerical research, EDF funded an experimental campaign (herein referred to as PEDRA campaign) including scaled-down physical models of rockfill dams with a dry-stone pitching.

A mixed three-dimensional DEM-FEM (discrete element method - finite element method) approach is suggested to better understand the seismic resistance of rockfill dams with a dry-stone pitching while benefiting from earlier numerical simulations on dry-stone retaining structures (Deluzarche et al., 2004 [1]; Chen et al., 2012 [2]; Oetomo et al., 2014 [3]; Savalle et al., 2020 [4]). A validation of the DEM-FEM technique for these structures is offered based on the PEDRA campaign. *PFC3D* and *FLAC3D* (ITASCA software) were utilized for this purpose, respectively for the dry-stone pitching and the dam body. Another objective is to study the scale effect by modeling of real-scale dams equivalent to the scaled-down ones and then compare their results. In addition, the effect of the berm, usually found on the downstream face of such dams, on their resistance and displacements is quantified.

2. Modeling OF Scaled-Down Experiments

Despite several numerical attempts to simulate such dams, the behavior of most steep dams with a dry-stone pitching remains an open problem. Previous fully two-dimensional DEM simulations [1] raised the issue of their validity in the absence of a database for their validation. For this reason, EDF funded scaled-down experiments in 2014 devoted to a better understanding of the role of the pitching on the dam stability. In this study, a validation of a numerical approach is proposed based on those experiments.

2.1. Description of PEDRA Experiments

The physical models are 1/10 scaled-down ones whose dimensions are inspired by specific dams located in the Pyrenees Mountains, France. They have dimensions of 2.25 m in width, 4.2 m in length, and a slope of 45° on both faces (Figure 1). Skilled dry-stone masons constructed them within the bucket of a crane truck. The foundation of the dam is made of rockfill, which is supported by steel rods that are welded to the truck at the base of the two dam sides. To reduce friction between the dam and the side walls, steel plates were welded to the two inner bucket sides before being coated with polyane. Finally, the bucket was rotated using the crane truck in pseudo-static testing till failure.

The same geometry and backfill properties (porosity of about 0.4 and uniformity coefficient of 2) were used to construct four different dams. The distinctions lay in the dry-stone pitching properties, including stone nature, thickness, block size, and contact with the backfill. For example, in case 4, the pitching was formed of two layers of granite blocks (5×5×10 cm3) and in case 3, some pitching stones were anchored within the backfill.

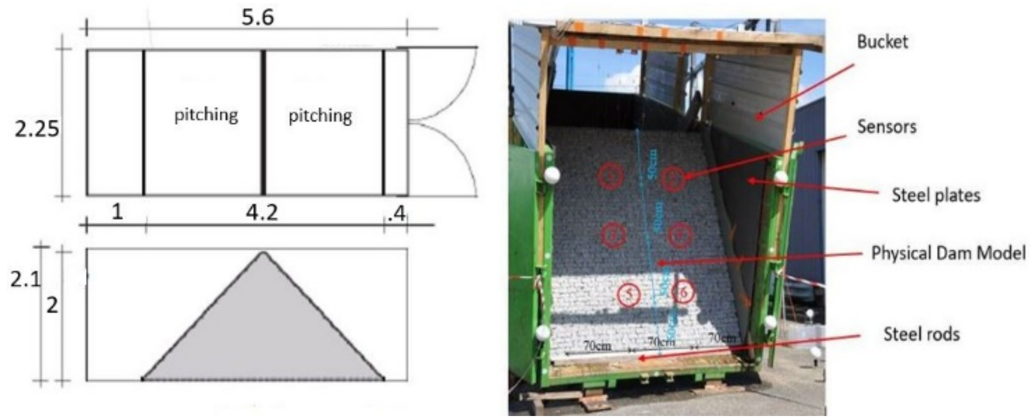

Fig. 1: Example of PEDRA scaled-down physical model and its dimensions in meters

2.2. Numerical Simulations

The dry-stone pitching was modeled using a discrete element method based on *PFC3D* software, whereas the dam body (rockfill) was modeled using a continuum approach with *FLAC3D*: a coupling between the two software was developed. Figure 2 displays the four modeled cases from the PEDRA campaign along with the pitching properties (P.S.D: pitching surface density, stones material and number of layers).

Concerning the boundary conditions, the two lateral sides of the dam body and the pitching were fixed in the y-direction with no friction applied to them to simulate the presence of the two polyane-covered bucket sides. The first bottom row of blocks was fixed on both faces. The dam sits on a rigid fixed foundation with a frictional interface between them.

The simulation was divided into several steps: The dam body was first created with *FLAC3D* and gravity was applied until equilibrium is reached. Then, the dry-stone pitching is generated using *PFC3D* on both dam faces where the coupling between both software starts involving an interface between the blocks and the dam body. A new equilibrium is found under gravity. After construction, the tilting was simulated by rotating the gravity vector with an increment of 1°. A convergence criterion was built to detect failure. It is based on unbalanced forces (ratio between the unbalanced forces and the total forces) and the pitching kinetic energy. Six sensors were placed on the downstream face to trace the displacements throughout the rotating process (Figure 2).

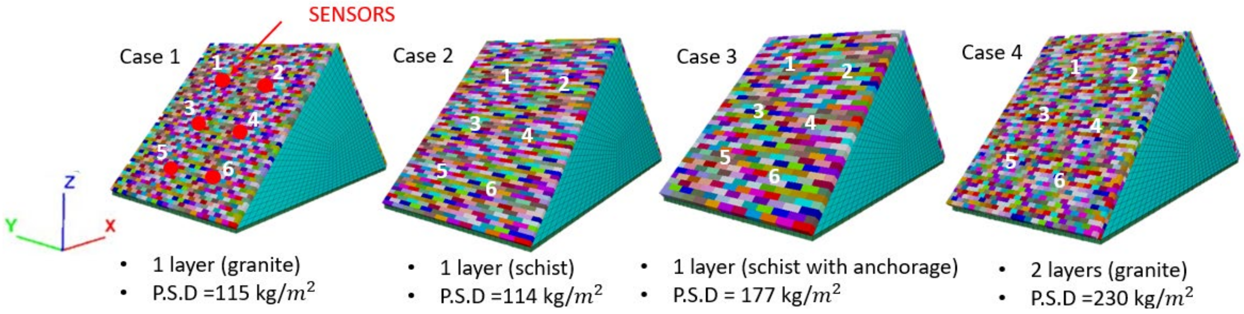

Fig. 2: Numerical models of the four PEDRA cases, pitching properties and position of six sensors

The constitutive model used for the dam body (backfill) is LK Enroch. It is an elastoplastic model developed by EDF with isotropic and deviatoric plastic mechanisms and an isotropic hardening. It involves 16 parameters which were calibrated by a trial-and-error method (The calibrated parameters can be found in [5]) based on experimental triaxial tests performed with a large cell (diameter of 1m). The results of the calibration along with the experimental curves are shown in Figure 3.

A linear frictional law was used to model the contacts between the pitching blocks and at the pitching-dam body interface. The effective modulus E^* for those contacts was found equal to 50 MPa and their stiffness ratio K^* equal to 2 (defined after a parametric study). A typical global damping (usually denoted Cundall damping) of 0.7 is used [6].

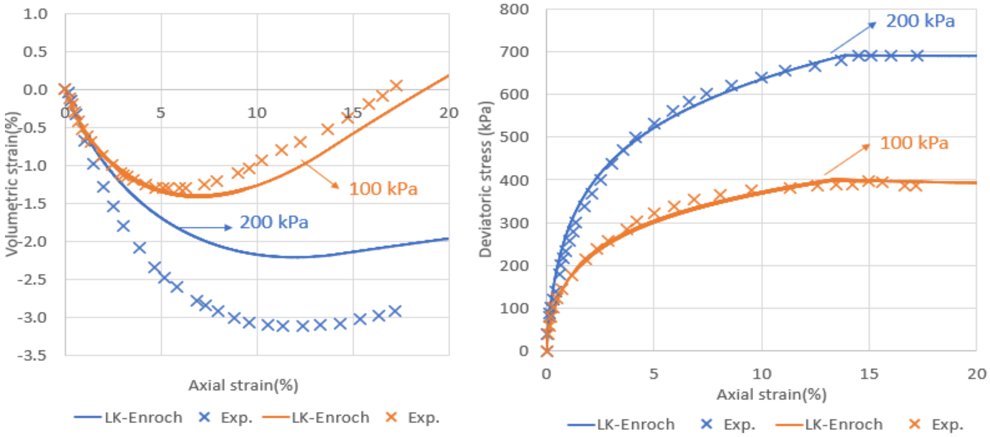

Fig. 3: Experiments and simulations of triaxial tests for the backfill material: volumetric strain (left) and deviatoric stress (right)

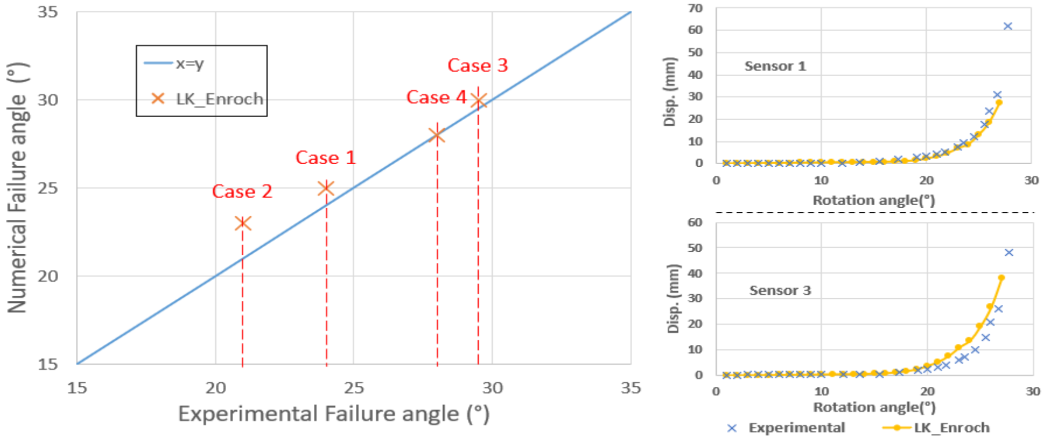

Fig. 4: Numerical and experimental failure angles for the four simulated cases (left) and displacements at two sensors in case 4 (right)

The numerical and experimental titling failure angles are given and compared in Figure 4 (left). The numerical model using LK Enroch was able to retrieve the experimental failure angles very accurately. In addition, the experimental and numerical displacements at sensors 1 and 3 in case 4 are given in Figure 4 (right) as an example of typical obtained results: the displacements obtained throughout simulations are very close to the experimental ones. To conclude, the mixed DEM-FEM numerical approach is considered as a relevant numerical tool to address the problem of stability of rockfill dams with dry-stone pitching.

Based on the obtained failure angle ($\theta_{failure}$) and the dam's slope angle (α=45°), a safety factor is calculated from Equation 1 for each dam. The results are shown in Table 1. Scaled-down dams with pitching have a high safety margin in the pseudo-static behavior ($F_\theta > 2.5$ for all cases) relatively to the case without pitching justifying the pitching's key role in such dams' stability. Indeed, the dam without pitching is close to failure with a safety factor of about 1.3. The larger safety factors obtained for case 3 and case 4 lie in the thicker pitching in case 4 and in both an equivalent thicker pitching and a larger equivalent friction angle at the backfill-pitching interface in case 3. More details about all the procedures of this study can be found in [5].

$$F_\theta = \frac{\tan(\alpha + \theta_{Failure})}{\tan(\alpha)} \tag{1}$$

Table 1: Failure angles and safety factors of the four cases with pitching in addition to a case without pitching

	No pitching	Case 1	Case 2	Case 3	Case 4
$\theta_{failure}$	7°	25°	23°	30°	28°
F_θ	1.28	2.75	2.48	3.73	3.27

3. Simulation of full-scale rockfill dams

In this part of the study, several cases of full-scale rockfill dams are simulated. As for the scaled- down dams, pseudo-static rotation tests are carried out to quantify the full-scale dam's resistance and safety factors are calculated. The effect of the pitching-backfill interface friction angle and the pitching weight on the dam's resistance is studied and analyzed. In addition, the scale effect on the behavior of rockfill dams with dry-stone pitching is presented and discussed. The scale effect study is done by comparing the behavior and resistance of the full-scale and scaled-down dams.

Three full-scale models which are equivalent to the scaled-down cases were progressively built in four stages:

- A reference full-scale case (case A) is considered (Figure 5): the dam has a pitching composed of one layer of granite drystones (equivalent to case 1 and case 2 of PEDRA campaign).

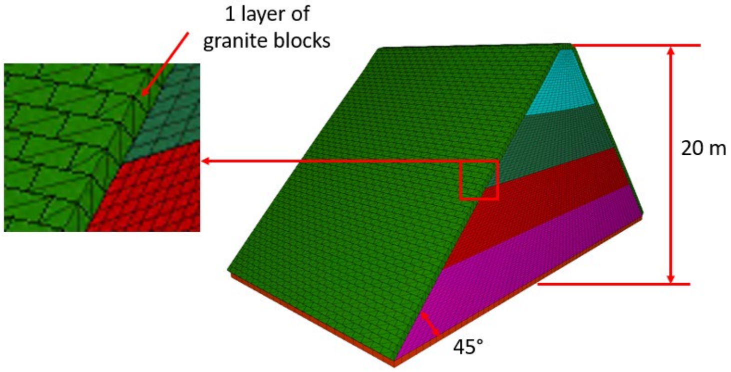

Fig. 5: Case A: a reference case for full-scale dams

- Case B is the same as case A but with anchorage of the pitching blocks inside the backfill. This anchorage is not modeled physically but rather by increasing the interface friction angle so that it becomes equal to the backfill friction angle.

Indeed, we state that the mechanical interface is shifted towards the backfill, a statement that is commonly taken in the case of a rough retaining wall-backfill interface. This case is equivalent to case 3 of PEDRA campaign.

- Case C has a pitching composed of two layers of granite drystones laid one above each other which is equivalent to case 4 of PEDRA campaign.

Since the 1/10 scaled-down dams have 2 meters in height, full-scale dams of 20 meters in height and 45° slope angles with respect to the horizontal for both the downstream and upstream faces have been chosen. The porosity of the backfill is taken equal to 0.4 whereas the porosity of the dry-stone pitching is equal to 0.2 which are considered average values for these types of dams [7]. The blocks of the pitching have an average dimension of 50×50×100 cm^3 (pitching thickness is 50 cm). 22 blocks are used along the dam width which is the same number as PEDRA scaled-down models. The linear frictional law is used to model the contacts between the pitching blocks and at the pitching-dam body interface. Moreover, the boundary conditions applied on the full-scale models are similar to the ones found in the scaled-down models.

Regarding the parameters of the backfill constitutive model LKE, model parameters identified in the scaled-down models were used except for some parameters which were adapted to the size of the full-scale rockfill material. The parameters influenced by scale effects are typically Young's modulus E and the compressive strength σ_c. Frossard's scale effect approach [8] is used according to the following equations:

$$\sigma_{c,B} = (\frac{d_B}{d_A})^{-3/m}.\sigma_{c,A} \text{ and } E_B = (\frac{d_B}{d_A})^{-3/m}.E_A \quad (2)$$

where:

- $d_B = D_{50,B}$ = 30cm is the average size of the full-scale rockfill [7]
- $d_A = D_{50,A}$ = 4cm is the average size of the scaled-down rockfill
- m: Weibull coefficient, average =6 [8]
- E_B and E_A are the Young's moduli of the full-scale and scaled-down rockfill respectively
- $\sigma_{c,B}$ and $\sigma_{c,A}$ are the Young's compressive strengths of the full-scale and scaled-down rockfill respectively

As for the scaled-down dams, simulations of pseudo-static rotation tests were carried out by rotating the gravity vector with an increment of 1° until failure is reached. The failure angles and safety factors obtained in full-scale scale simulations are shown in Table 2. The key role played by the pitching in the dam stability is again emphasized. The dam fails without pitching even before rotation starts since it has a friction angle (≈ 42°) less than the dam's slope angle α=45° (F_θ <1). This safety factor increases to values higher than 1.6 in the different full-scale tests with pitching.

An effect of the pitching-backfill interface friction angle on the dam's resistance is demonstrated. The case with higher interface friction angle (case B) gave a slightly higher failure angle than case A.

The role played by the pitching weight was also studied. Case C which has two layers of blocks for the pitching has a significant higher safety margin than case A which has only a layer of blocks.

Finally, scale effect on such dam's resistance can be noticed. Full-scale dams are associated to significant lower failure angles than the scaled-down ones. The safety factors of the studied full-scale dams are in the range of 1.6 to 2 whereas the safety factors of the studied scaled-down dams are in the range of 2.5 to 3.7. This difference was expected due to the higher mean pressures in full-scale dam's which decreases the rockfill peak resistance. The internal friction angle for the rockfill scaled-down dams was equal to 52° whereas it was identified equal to 42° in the full-scale dams. This phenomenon was studied and justified in different past studies [9] [10].

Table 2: Failure angles and safety factors of the studied full-scale dams

	No pitching	Case A	Case B	Case C
$\theta_{failure}$	-3°	14°	15°	18°
F_θ	0.90	1.66	1.73	1.96

4. Effect of a Berm on the Downstream Face

A dam berm is a horizontal shelf that breaks the continuity of the dam's slope. It is widely found in rockfill dams with dry-stone pitching in France mainly on the downstream face. There exists rockfill dams with one, two or even more berms depending on the height of the dam. The berms on such dams have a width of 1 to 2 meters based on several examples provided by the stakeholder "Electricity of France" [7].

The effect of the berms on such dams' stability is ambiguous, especially with the presence of hand-placed drystones on those dams' faces. The discontinuity of the drystone pitching due to the berm may have some effect on the dam's stability where the forces transferred within the pitching blocks are interrupted. It may lead to a decrease in the stability role of the pitching.

To better understand the effect of the berm on the safety of rockfill dams with dry-stone pitching, case A dam was modified in which we added a berm of 1.2 meters of width on the downstream face at the mid-height of the dam. The dam was reconstructed with a berm in four stages as before. The horizontal and vertical displacements at the end of the dam construction with a berm are obtained and compared to case A. They are given side by side in Figure 6 together with the horizontal and vertical displacements at crest and at mid-height sides.

The presence of the berm leads to an increase of the vertical displacement at the crest from 17 to 20cm. Part of the backfill slides to the downstream side (where the berm is found) which induces higher displacements at the crest. This also leads to higher vertical displacements at the berm (from 2cm without berm to 4cm with berm).

For case A, due to its symmetrical shape, the horizontal displacement at crest is null. On the contrary, a 3cm extra downstream horizontal displacement was obtained at crest for the case with berm which was also found at berm level.

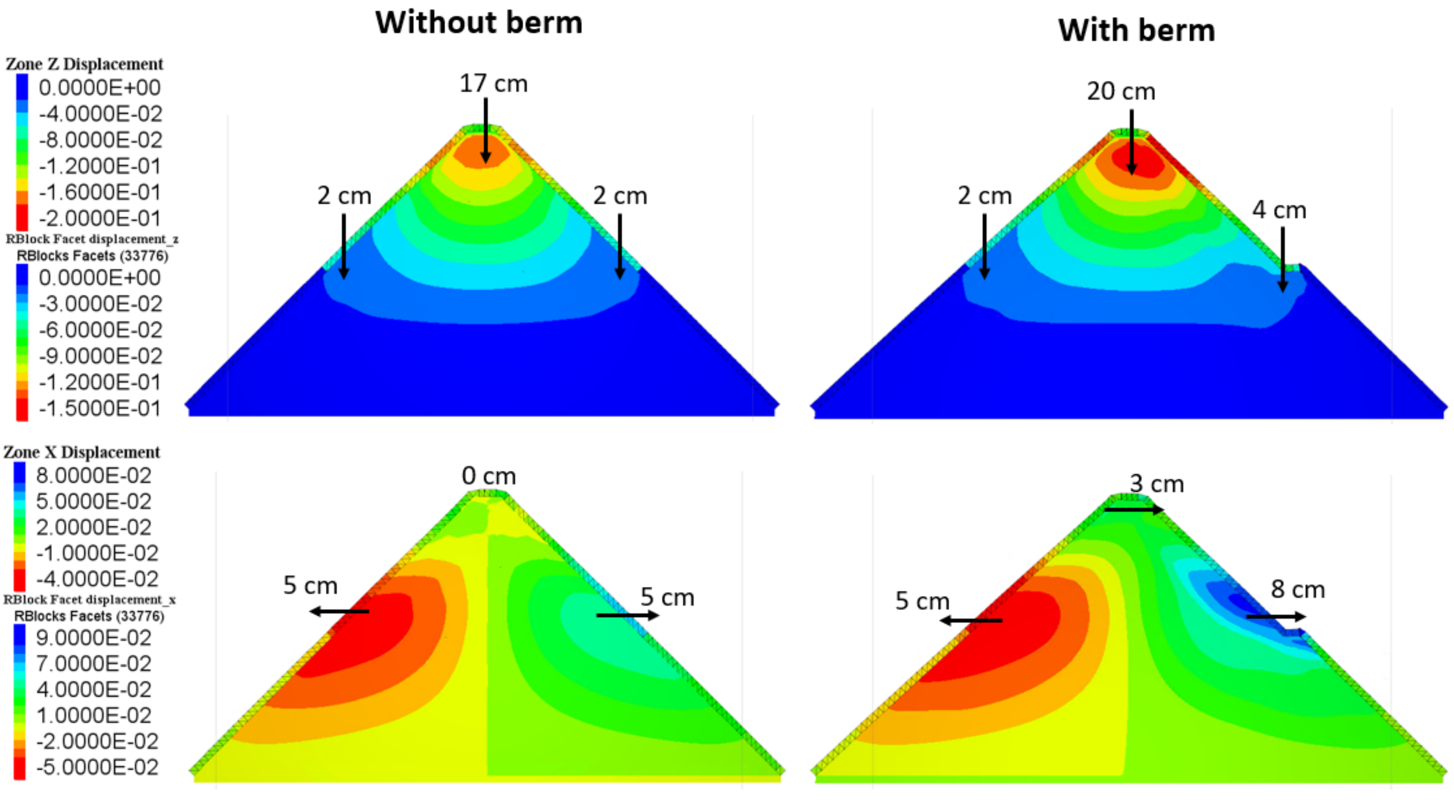

Fig. 6: Vertical and horizontal displacements at the end of construction of a rockfill dam with dry-stone pitching: without berm (left) and with berm (right)

After construction, pseudo-static rotation tests were carried out on both dams. The dam with the berm failed at a rotation angle of 11 degrees ($F_\theta = 1.5$) which is 3 degrees less than the dam without the berm ($F_\theta = 1.7$). Therefore, the effect of the berm on such dams' resistance cannot be neglected since it decreases the dam's safety factor. The berm induces a discontinuity separating the pitching into two parts (upper pitching and lower pitching) that do not behave as a whole. In Figure 7, the failure position of the dam with and without the berm is shown. The dam without the berm has a failure surface that emerges on the pitching at almost one-third of its height whereas the dam with the berm failed mainly at the berm area. The upper pitching actually lays on the backfill and tends to punch it the at berm location. Lateral stresses which tends to load the top part of the lower pitching are generated. This phenomenon also contributes to higher displacements in the dam with the berm. In Figure 7, the two cases are compared at two rotation angles (7 and 10 degrees) where this difference is clearly noticed.

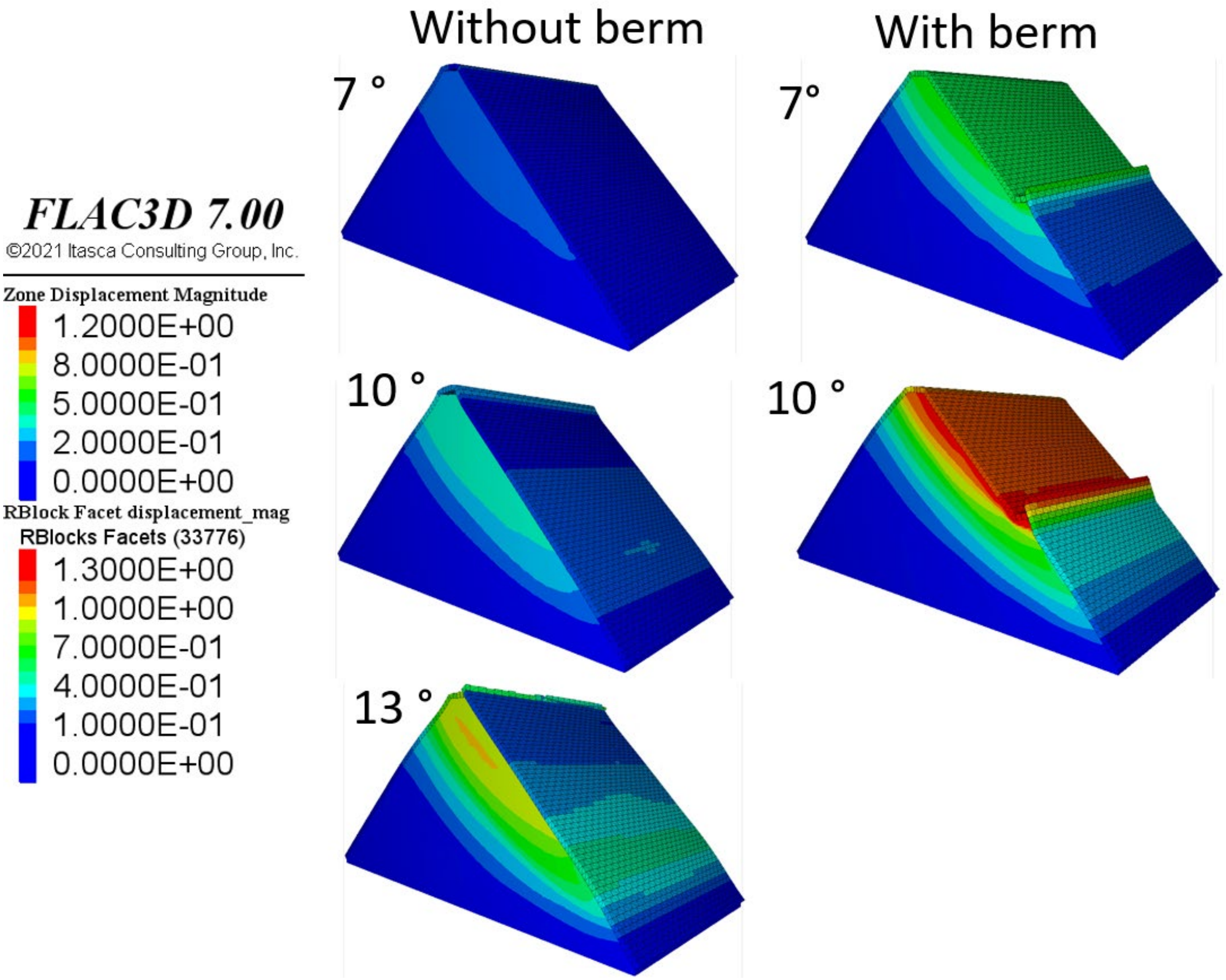

Fig. 7: Displacements of the studied rockfill dams with dry-stone pitching at several rotation angles before failure: without berm (left) and with berm (right)

5. Conclusion

A mixed DEM-FEM approach, involving DEM for the pitching and FEM for the dam body, was used to provide a numerical model for studying the mechanical behavior of rockfill dams with a dry-stone pitching. By simulating four distinct cases that were examined over an experimental campaign, this technique was validated. It involved tilting scaled-down rockfill dams with dry-stone pitching in a truck crane until they collapsed.

Then, three full-scale rockfill dams with dry-stone pitching were modeled and studied. This study allowed to justify the significant role played by the pitching and its weight in the stability of such dams. The effect of the pitching-backfill interface friction angle on the resistance was found less significant than that of the pitching weight.

The scale effect on such dams' resistance was clearly highlighted. The dam's resistance decreased remarkably when scaled up. Developing higher pressures inside the full-scale dams decreased the backfill internal friction angle and thus its resistance.

Finally, the impact of a berm on such dams' resistance was also studied. The presence of a berm highly decreased the dam's resistance: lower failure angles were obtained and higher displacements were observed. A Berm induces a discontinuity in the transfer of forces throughout the pitching and represented a weak point where failure is triggered.

Acknowledgements

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