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Applications of Numerical Methods in Design and Evaluation of Overtopping Protection Systems

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ABSTRACT

The development of overtopping protection systems often requires detailed analyses of complex physical phenomena. This hinders the comprehensive knowledge of their behavior, and therefore the development of suitable design criteria. In recent years, the authors have developed and validated different methods, combining continuous, particle and discrete numerical techniques, to obtain accurate and reliable solutions of different numerical problems involving fluid-soil-structure interaction. In this contribution, some applications of these methods to the study of dam protection against overtopping are presented. The main advantages of this approach include the ability to extract results of the governing variables (pressure, velocity) at any location of the domain, and the possibility to consider scenarios without the restrictions of the experimental facilities (flow rates, size, scale effects).
In particular, the contribution gathers examples of application of numerical methods in a) analysis of rockfill dam stability against overtopping, including seepage evolution and deformation of the downstream shoulder, and b) stability analysis of wedge-shaped-blocks subjected to vandalism.

Keywords: *Numerical modeling, Spillways, Wedge-shaped blocks, Overtopping protection, Rockfill dams, Fluid-soil-structure interaction*

1. INTRODUCTION

Numerical simulation is becoming increasingly important in several areas of engineering. In recent years, we have experienced an important growth in the knowledge in computational mechanics, and several innovative techniques have been developed and validated. This aspect, together with the increase in computational power and efficiency of common personal computers, has made possible the simulation of several complex multi-physic phenomena in a reliable and efficient way.

Today, a joint experimental-numerical approach is a fundamental part of the comprehensive analysis of many physical phenomena, including those related to dam engineering.

Numerical simulations allow an important saving in money and time when designing experimental campaigns. Parametric studies can be easily carried out to identify the important aspects to be analyzed experimentally, sensibly reducing the number of needed experiments. Moreover, simulations naturally overcome scale effects that are still the main drawback of experimental campaigns. On the other hand, numerical models contain theoretical simplifications, so experiments remain essential for validating and calibrating computational tools.

There is increasing concern worldwide about the environmental risk related to the devastating action of water. Unfortunately, this trend is likely to accelerate in the coming decade, according to predicted climate change scenarios.

Indeed, many dramatic floods have recently occurred worldwide. To increase the safety of critical structures like dams and dikes, new protective features and other modifications should be considered to minimize the damage caused by floods. In this field, experimental modeling is seriously affected by the difficult scaling of the materials involved and by the limited flow capacity of laboratory facilities compared to full scale structures. For this reason, it is worth considering the numerical simulation of the free surface and seepage flow for a correct evaluation of their hydrodynamic effects on dams.

If climate change represents a serious risk for critical structures, we cannot forget the equally important and unfortunately increasing risk of human-caused terrorism and vandalism. Since the late 1990s several security managers from the major hydroelectric dam companies have organized technical panels for the evaluation of possible vulnerability of their facilities against possible human malevolent interventions. Anthropic risk ranges from small vandalistic acts to extreme terrorist attacks and the consequences can be extremely dramatic, especially considering the sudden and unexpected nature of the acts.

The current work aims to present an overview of some recent applications of innovative numerical techniques developed to solve practical issues related to the design or maintenance of protective features of dams in both natural and human-induced risk scenarios.

Two different problems have been analyzed and will be presented in this work. First, the structural response of rockfill dams in extreme flooding scenarios is studied using a coupled particle based method developed in Kratos Multi-physics (Dadvand et al., 2010). Second, a stability analysis is presented for wedge-shaped-blocks subjected to vandalism.

2. KRATOS MULTIPHYSICS

Kratos Multi-physics is an Open-Source framework developed at the International Center for Numerical Methods in Engineering (CIMNE) for the implementation of numerical techniques for the solution of engineering problems (www.cimne.com/kratos). It is written in C++ and is designed to allow collaborative development by large teams of researchers focusing on modularity as well as on performance. Its ultimate goal is to simplify the development of new numerical methods.

Kratos has a kernel-applications approach to facilitate its use by non-expert developers and maximize its reusability by developers. The kernel includes all the basic ingredients of a code (from data structures, to solvers or parallelization features, just to mention a few), while the applications contain the physics of the specific problem (some classical applications are Fluid Dynamics and Structural Mechanics, while examples of novel applications are Mixed formulation, PFEM, DEM …).

All of the applications presented in this paper have been developed in the Kratos environment. GiD (www.gidhome.com) is the pre and post processing tool, developed at CIMNE, used for visualization and preprocessing purposes.

3. ANALYSIS OF ROCKFILL DAM STABILITY AGAINST OVERTOPPING

3.1 Motivations

The rehabilitation of existing dams and their safety analysis are presently open fields of research. In fact, in many countries, the design criteria of these structures have recently been revised with the intention of increasing safety levels when faced with exceptional flooding.

Many dams and dikes now exhibit a higher potential to experience overtopping during exceptional flood events than was intended when they were originally designed. Revised and more accurate hydrologic studies and climate change induced by global warming are among the primary causes of increased overtopping risk.

While in a concrete dam, an overflow does not easily affect the integrity of the structure, for an embankment dam in most cases it compromises the dam body. If a dam or dike fails, loss of life and economic damage are direct consequences of such an event. Early warning is therefore crucial for saving lives in flood-prone areas. That is the reason why an increasing interest is rising on the study of rockfill and earthfill dams, termed embankment dams, during extreme phenomena.

The analysis of the possible outcome of an accidental overspill is still difficult or very imprecise and the necessary economic measures for solving the problem are often inefficient. An appropriate computational method will help to improve the economic value of the investments in dam safety and in emergency plans for embankment dams. It should simulate the sudden dynamic change in the seepage and flow condition and predict the subsequent onset and evolution of breaching in the rockfill slope.

3.2 Numerical modelling

A coupled numerical model has been developed by the authors in the Kratos Multi-physic framework. First of all, an efficient and parallel computational fluid dynamic code solving the Navier-Stokes equations was developed (Rossi et al., 2013). The tool is able to track the evolution of the free surface using a level set technique, and hence it can be used for hydraulic analysis of dam spillways (e.g. Salazar et al. 2013, Morera et al. 2014, Salazar et al., 2015). Moreover, the formulation was conceived to be able to take into consideration the presence of a rockfill-like porous material and to simulate the seepage evolution (Larese et al., 2015a, 2015b). Seepage in rockfill is extremely different from seepage in soils due to the high permeability of the material that allows a fast evolution of the turbulent flow within the rocks. This turbulence is simulated at a macro scale with a non-linear resistance law governing the relation between velocity and the hydraulic gradient (Larese et al., 2015a).

This computational fluid dynamic (CFD) code was coupled with a structural algorithm for the evaluation of the dam response to the hydrodynamic transient effects. The structural algorithm implements a visco-plastic model to capture the solid-fluid-like transition which triggers the beginning of failure of the rockfill downstream slope. A particle based technique has been used for naturally treating the large deformations the mesh is subjected to during the failure process (Larese et al., 2012). First and second generation particle finite element method (PFEM and PFEM2) have been used for this purpose, giving encouraging results.

A detailed description of the algorithm can be found in (Larese et al., 2012, 2013, 2015a).

3.3 Results

An extensive validation of the developed code has been carried out using the experimental data obtained by Prof. Miguel Ángel Toledo’s group at the UPM (Larese et al., 2011, 2013, Moran, R., 2015, Toledo et al. 2015).

Figure 1 shows the results of the coupled analysis in the case of a homogeneous small scale dam made of gravel material ($D50 = 3.5$cm, porosity $n = 0.4$) which was tested at the UPM laboratories. The height of the dam is 1m and the upstream and downstream shoulder has a slope 1.5H:1.0V. With such a steep slope the main failure mechanism is mass sliding. Superficial erosion has a relevant impact only on the transport of the already failed material away from the toe. The formation of slip lines during the transient phase is shown in Figure 2.

Figure 1 and Figure 2 show the transient phase in the case of an incoming discharge of 90.68 L/s. Other incoming discharges have been considered and the advance of failure at the end of the simulation was compared with the experimental measurements. By definition, the advance of failure (B) is the distance from the undeformed toe of the dam to the horizontal projection of the highest point of the downstream shoulder that moves. The results of the comparison are shown in

Table 1. The error decreases with the increment of the incoming discharge arriving to capture with a high fidelity the so called *failure discharge* (i.e., the discharge for which the failure achieved the crest of the dam). The maximum error is lower than 4.5% and, considering that the experimental measurements are affected by a 10% error, this is an admissible accordance.

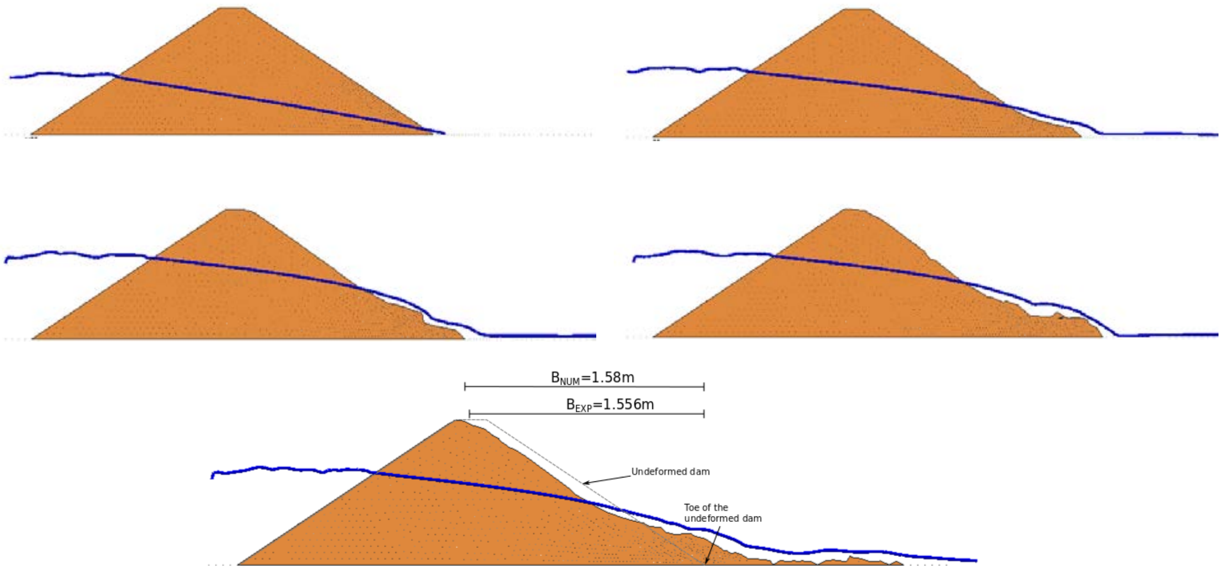

Figure 1 Evolution of the free surface/seepage line (in blue) and of the deformation of the downstream shoulder in a homogeneous dam for an incoming discharge of 90.68 L/s.

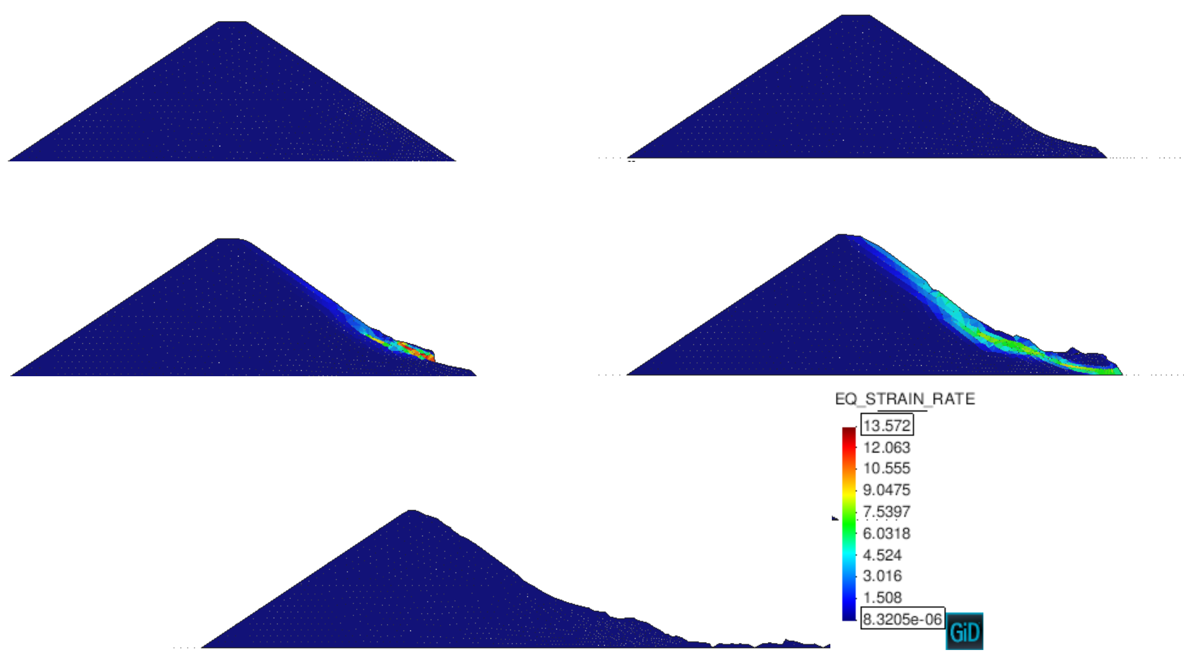

Figure 2 Evolution of the slip lines during the failure process of an homogeneous rockfill dam without internal core or upstream impervious layer for an incoming discharge of 90.68 L/s.

Table 1 Numerical and experimental comparison of the advance of failure (B_{num} and B_{exp} respectively) for different values of the incoming discharge.

Q (l/s)	B_{exp}	B_{num}	Error
51.75	0.71	0.68	4.2%
69.07	1.08	1.04	3.7%
90.68	1.556	1.58	1.3%

3.4 Conclusions and future work

A coupled model to capture the beginning of failure in rockfill dams was presented. A computational fluid dynamic (CFD) code for the analysis of both free surface flows and seepage in highly permeable materials (rockfill-like) was coupled with a moving-mesh structural code for evaluating the dam response. The structural code is based on the Particle Finite Element Method (PFEM) to allow managing large deformation in a natural way. A viscoplastic constitutive law is considered for the rockfill.

The numerical experimental comparison shows promising results.

In the future the possibility to evaluate the superficial erosion will be included. This will allow an accurate analysis also of gentle slopes (3H: 1V) where this failure phenomena is predominant. On the other hand the effect of air, not considered in the CFD code at the moment, will be included in the fluid dynamic analysis. This will allow a more accurate study of the water-air interaction on the seepage and free surface line when interacting with rockfill.

4. STABILITY ANALYSIS OF WEDGE-SHAPED BLOCKS SUBJECTED TO VANDALISM

4.1. Motivation

Wedge-shaped block (WSB) spillways constitute a promising technology for cost-effective design of embankment dam spillways, since they can be located over the downstream dam shoulder. Several application examples exist (e.g. Morán and Toledo, 2014), which have shown an appropriate behavior. However, additional research on this technology is still necessary for further expansion (Morán and Toledo, 2014). One of the major concerns to be considered for determining the size of the blocks is the threat of vandalism or removal of blocks (Hewlett et al, 1997).

The probability that a block is removed from its position in the spillway is obviously lower for heavier blocks. In particular, the risk is significantly reduced if the block weight prevents it from being removed by manual means. Furthermore, the necessary force is greater than the weight of each block, due to the overlapping between consecutive rows. The aim of this work is to calculate the value of that force and its relation to the weight of the block.

4.2. Numerical modelling

The numerical simulation of WSB removal is a dynamic problem involving large deformations that requires consideration of the interaction between adjacent blocks: the displacement of those in the upper rows, and interaction with those on the sides and bottom, which generate frictional forces. All these phenomena can be easily modeled with the Discrete Element Method (DEM). In the DEM, the domain of analysis is discretized into rigid particles with known dimensions (frequently spheres), whose movement is defined by the standard rigid-body dynamics equations, under the force of gravity and contact forces with neighboring particles or adjacent contours. The method is increasingly popular in various fields of engineering (e.g. Casas et al. 2015). We employed the implementation included in Kratos Multi-Physics (Dadvand et al., 2010, Santasusana et al., 2016).

To simplify the geometry and the computation of interparticle forces, spheres are usually employed in DEM to reduce computational cost. To consider non-spherical elements (as in the case of WSB), a method has been implemented to generate elements of arbitrary shape with sphere clusters. The result is a rigid element with the appropriate center of gravity and inertia (Fig. 3). Two blocks were considered in this work: that employed in Barriga Dam (Cluster 1), and a scaled one, similar to the standard Armorwedge™ block (Cluster 2).

The initial configuration includes 90 blocks distributed in 20 rows, resting on a rigid contour with slope 2H: 1V. The rows are numbered from downstream to upstream (Fig. 4). The displacement of both the side blocks and the topmost row is not restricted. Blocks in row 1 (the bottom row) rest on a rigid contour whose shape adapts to the downstream geometry, generating frictional forces that restrain the movement (Fig. 4).

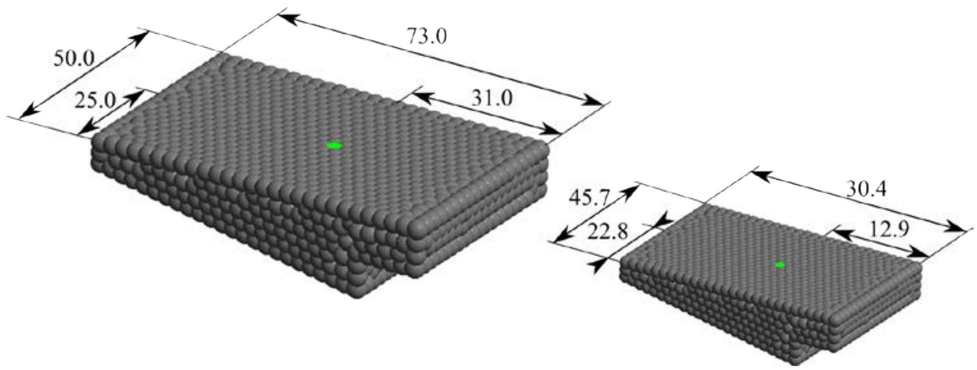

Figure 3. Blocks analyzed: main dimensions (cm) and point of application of the force. Left: Cluster 1 (1.09 kN). Right: Cluster 2 (0.22 kN).

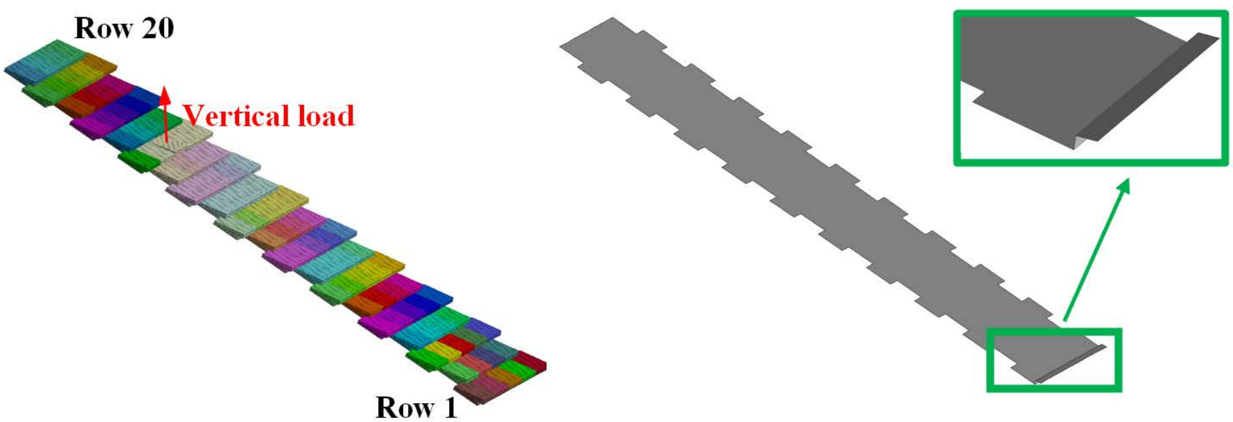

Figure 4. Left: array of blocks modeled. Right: rigid boundary which supports the blocks in the downstream toe.

In principle, each block is stable on the support layer due to the friction forces. In that ideal situation, there would be no contact between blocks in the slope direction, and the friction forces between the block to be removed and the downstream neighbors will be low. This effect is independent of the row in which the block is placed, except for row 1. In row 1, the force to be exerted shall be larger, since the downstream contour is not allowed to move. This hypothesis was modeled by assigning a value of 33 degrees to the angle of friction between the block and the supporting layer (enough to ensure static stability).

However, hydrodynamic forces during floods or inaccurate block placement may lead to contact between blocks in consecutive rows. In that situation, each block rests on the blocks located in the downstream adjacent row, and hence normal forces are generated. As a consequence, the friction force will be greater (since it is proportional to the normal contact force), and the block removal will require a higher load. Moreover, this load will depend on the block location within the dam shoulder, i.e., on the number of rows to the upstream boundary. This scenario was modeled by neglecting the friction between the blocks and the underlayer.

For each scenario (with and without block-boundary friction), the removal of the central block in rows 1, 3, 5, 9 and 15 was simulated: a vertical force was applied at the center of the visible portion of the upper face of the block (Fig. 3), whose magnitude was increased until the block was lifted. The corresponding value was recorded as the failure load.

4.3. Results

Figure 5 shows the failure load obtained for all of the simulated scenarios. The effect of the downstream boundary to cause a large failure load for row 1 is clearly observed in all cases. Although the removal of the heavier blocks (Cluster 1) requires a higher load as expected, the results are similar in terms of the unit failure load (*failure load/weight of the block*).

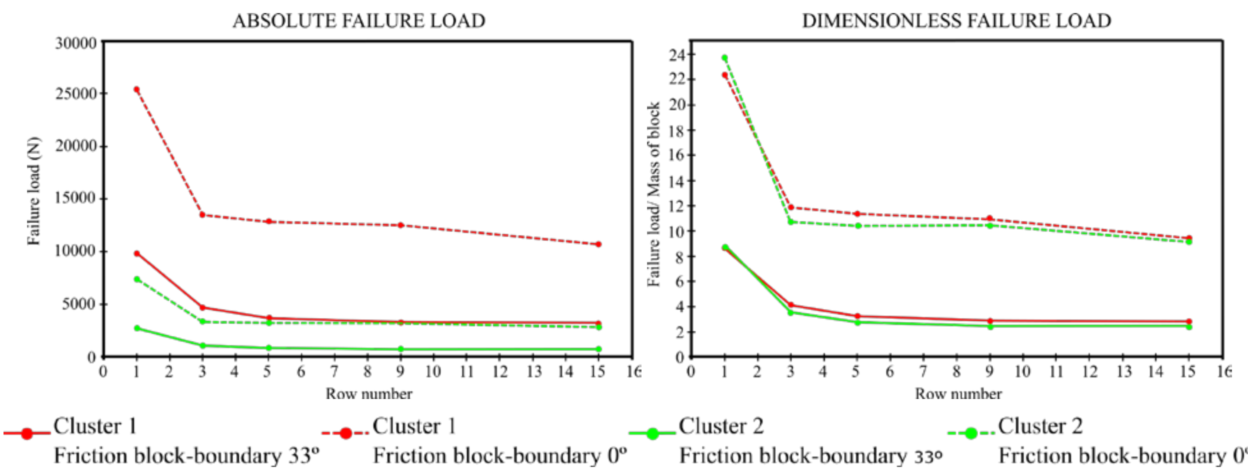

Figure 5. Failure load for the scenarios analyzed

The difference between scenarios with and without friction can be clearly observed in Figure 6. If the rows are compressed (null block-boundary friction), all of the surrounding blocks need to be displaced to remove that block under consideration. By contrast, when each block is stable, the pulled block tilts around its center of gravity and the neighboring blocks are mostly unaffected.

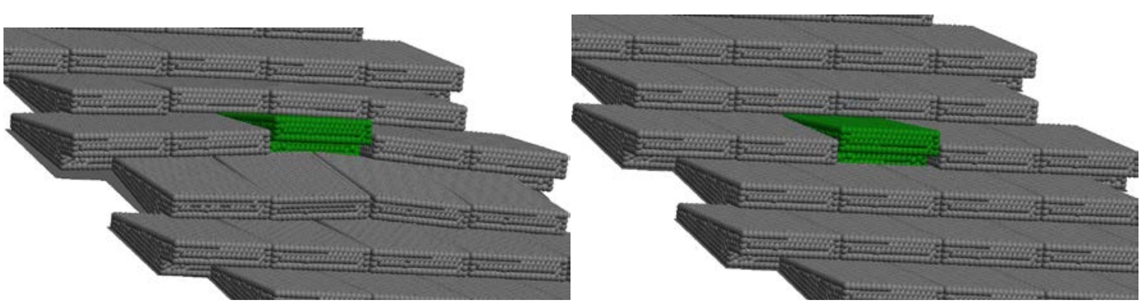

Figure 6. Example of failure pattern. Cluster 1, row 9 is pulled (green). Left: frictionless block-boundary contact; several blocks are displaced. Right: friction block-boundary of 33º; the displacement of the neighboring blocks is imperceptible.

The failure pattern was further analyzed. Figure 7 shows the blocks whose maximum vertical displacement during block removal was greater than 3 mm. It shows that for the frictionless case, a block removal requires 18 adjacent elements to be displaced over the chosen threshold. The same pattern is repeated for all rows but row 1, which rests on the fixed downstream boundary.

If the block-boundary friction is enough for the blocks to be stable and to avoid normal forces in the slope direction, only the two closest upstream blocks need to be displaced over 3 mm. Again, the same pattern is repeated for all rows but row 1.

These results confirm the relevance of the boundary condition (fixed boundary in row 1 in this case) and the block-boundary friction in the failure load.

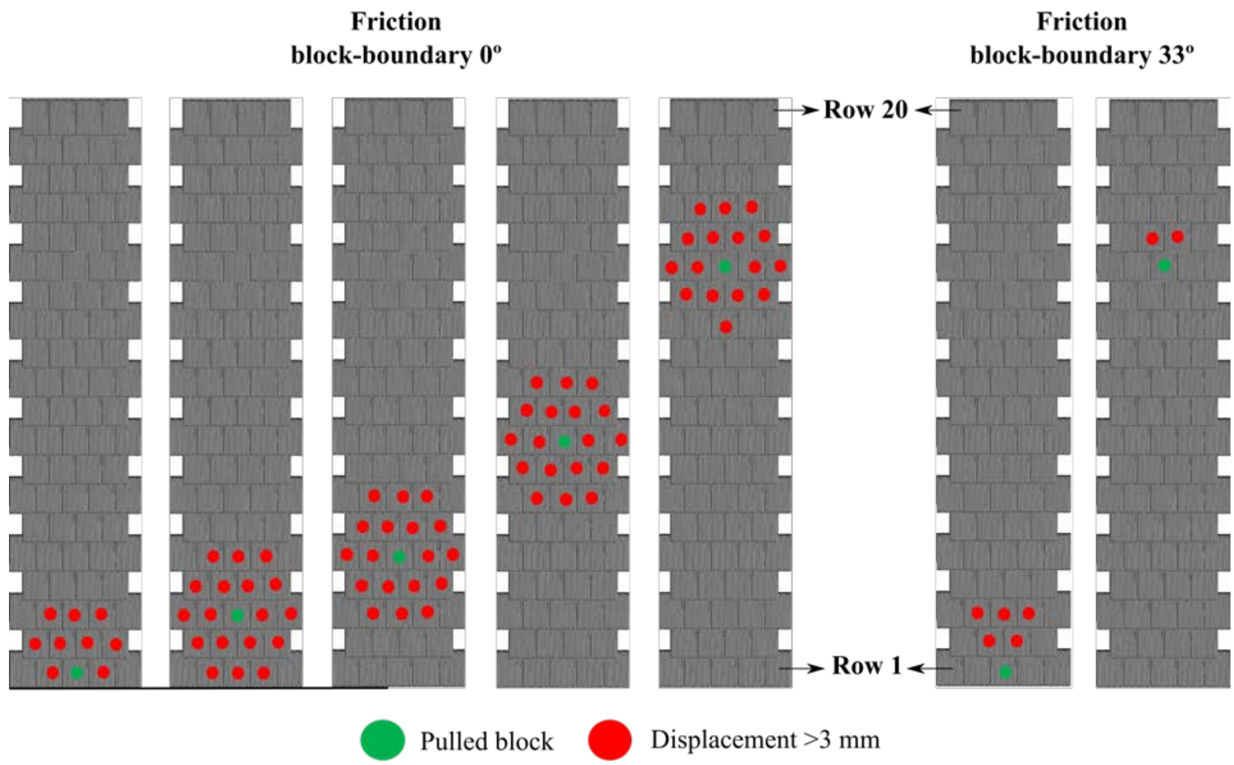

Figure 7. Cluster 1. Blocks with maximum vertical displacement over 3 mm during block removal.

4.4. Conclusions and future work

The results confirm that the force required to extract a WSB is significantly larger than its dead weight. The failure load/block weight ratio strongly depends on several factors:

- The boundary conditions – The downstream boundary was fixed in the cases analyzed, which resulted in a significant increase in the failure load for the blocks in row 1. This effect is slightly perceptible for row 3, and negligible for the upper rows. In the general case, both the lateral blocks and the upper row might also be fixed, which will result in different behavior.
- The contact forces between blocks – In the scenarios where the blocks are compressed, the failure mode is remarkably higher.

As expected, the failure load is proportional to the block weight. Nonetheless, the ratio failure load/block weight is sensibly constant for the two geometries analyzed, and depends only on the compression rate between blocks in the slope direction. The failure force obtained ranged from 2 to 24 times the weight of the block.

Future work will focus on analyzing the effect of a) the friction coefficient, b) the radius of the spheres in the cluster, c) the direction and point of application of the removal force, d) the downstream dam slope. Also, experimental tests will be performed to calibrate the numerical model.

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