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Hydraulic and Stability Analysis of the Supporting Layer of Wedge-Shaped Blocks

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ABSTRACT

Wedge shaped blocks (WSB) are attracting increasing attention as protection against overtopping for earth and rock-fill dams. However, there are limited examples of application and some aspects of the technology merit additional research and improvement. One key issue is the design of drainage and supporting layer for WSB protections. During overtopping, part of the overflow leaks through the joints between blocks, hence circulating through the granular material. The permeability and thickness of the supporting layer must be sufficient to prevent the flow from generating pressure on the bottom side of the blocks, which contributes to its destabilization. However, it must also be structurally stable to avoid undesirable deformations on the downstream face. Both the material permeability and the layer thickness determine the hydraulic behavior of this element. These, together with the weight of the blocks and the slope of the downstream face, directly influence mass and block stability. These aspects should be taken into account for the numerical modeling of seepage through the supporting layer. To this end, an application of the open source software Kratos Multi-physics was employed. A parametric study was conducted to quantify the influence of each design variable in the safety factor against mass sliding of the supporting and drainage layer.

Keywords: *Leaks, Mass sliding, Numerical modeling, Spillway, Supporting layer, Wedge-shaped blocks.*

1. INTRODUCTION

The wedge shaped blocks (WSB) protections were born at the Moscow Civil Engineering Institute in the late 60s of the XX century. Although the results of the first tests were promising, this technology was slowly developed and limited to specific projects in the former USSR (Pravdivets and Slissky, 1981). About twenty years ago, further investigations were carried out in the U.K. (Hewlett et al., 1997), USA (Frizell, 1997), Portugal (Relvas and Pinheiro, 2008) and Spain (Caballero et al. 2015). This proceeding shows some results of the Spanish research (ongoing) concerning the hydraulic capacity and stability of the granular layer on which the blocks are placed.

One of the most important aspects to design effective WSB protections is the definition of an appropriate supporting granular layer for drainage. This layer collects seepage between block joints and through the aeration orifices. If its hydraulic capacity is inadequate to evacuate this seepage, an uplift pressure would occur on the underside of the blocks, which could potentially affect its stability. A scheme of operation of WSB protections is shown in Figure 1.

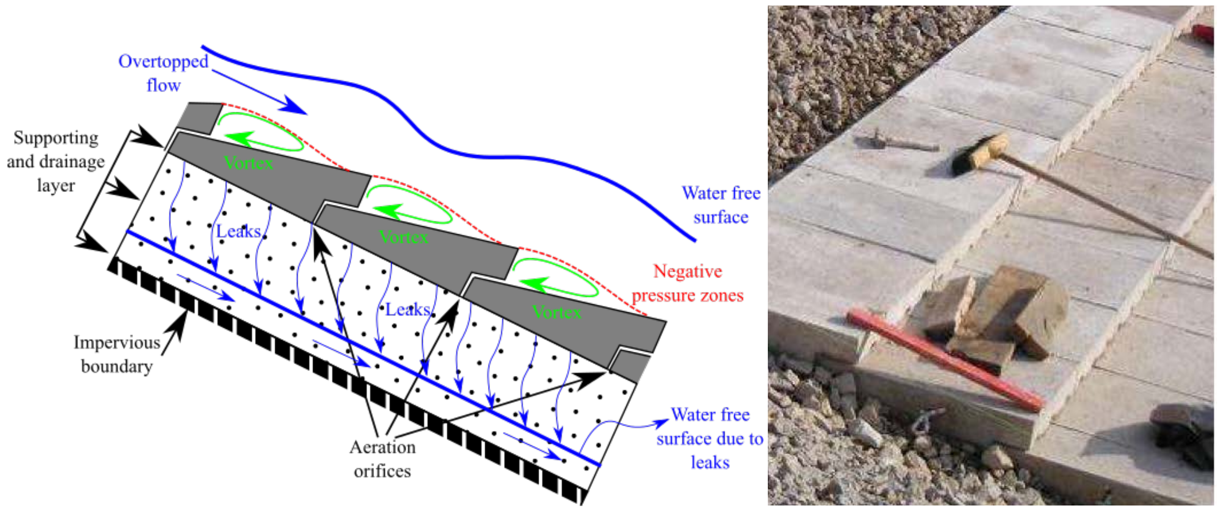

Figure 1. Left: scheme of operation of WSB protections, including the role of the supporting layer. Right: detail of the construction of WSB protection (Barriga Dam), the joints between adjacent blocks and the granular drainage layer under the blocks are shown.

In the context of this research, several numerical simulations were carried out to model the seepage through the drainage layer, in order to estimate the required layer thickness to convey seepage flows without creating uplift pressures. Moreover, a formulation to calculate the safety factor against mass sliding for a partially saturated layer was developed. It was applied to obtain the relationship between the safety factor against mass sliding and the hydraulic capacity of a drainage layer, for several granular materials, slopes and wedge shaped blocks.

2. METHODOLOGY

2.1. Numerical Code

The numerical code used for all simulations was one of the applications implemented in the open source software KratosMulti-Physics (Rossi et al., 2013, Larese et al., 2015), which solves the full Navier-Stokes equations according to an Eulerian scheme. This numerical code allows to define the flow resistance by the parabolic expression shown in Eq. (1), which is adequate for numerical modeling of granular materials (Volker, 1969). This code has already been successfully applied in spillway hydraulics (e.g. Salazar et al. 2013, Morera et al. 2014, Salazar et al., 2015) and dam failure analysis (Larese et al., 2013).

$$i = av+bv^2 \tag{1}$$

where i is the hydraulic gradient, a and b are coefficients which depend on the material properties and v is the seepage velocity.

The two-dimensional nature of the seepage flow through the drainage layer allowed it to be modeled by means of 2D numerical simulations. An unstructured triangular mesh was used in all the simulations, with homogeneous spatial distribution and a maximum element size of 0.05 m. A representative example of the numerical models is shown in Figure 2.

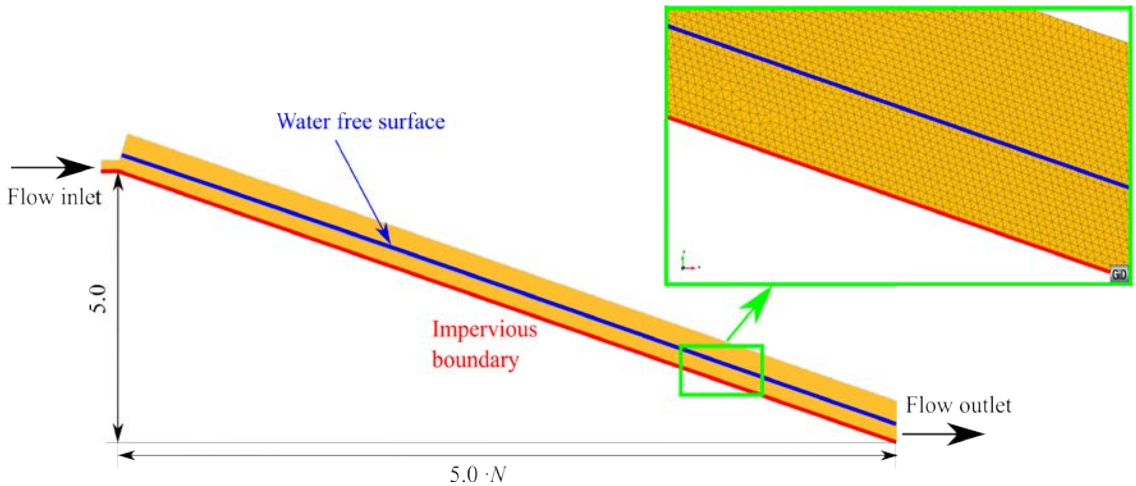

Figure 2. Example of numerical simulation carried out in this research. The yellow zone depicts the computational domain of granular material, and the blue line defines the position of the free surface. Where *N* is the slope. Dimensions (m).

2.2. Scenarios Analyzed

The models represent the downstream shoulder of an earth or rockfill dam. Hence, four typical values for the slope of these dam typologies were tested, namely N=1.5, 2, 2.5 and 3.

Three granular materials have been considered (M1, M2 and M3), which represent three materials potentially used for construction with average diameter of (d_{50}) 12.6, 35.04 and 45.5 mm. Their main properties are shown in Table 1.

Table 1. Properties of the three gravels simulated. d_{50} average diameter, $\gamma_{e,sat}$ saturated specific weight, $\gamma_{e,dry}$ dry specific weight, ϕ friction angle, n porosity.

Material	d_{50} (mm)	$\gamma_{e,sat}$ (kN/m^3)	$\gamma_{e,dry}$ (kN/m^3)	ϕ (º)	n
M1	12.6	18.34	14.32	36.94	0.41
M2	35.0	18.49	14.47	41.97	0.41
M3	45.5	18.98	14.96	41.66	0.41

San Mauro et al. (2015) defined a parabolic expression for the flow resistance of materials M1 and M2 by means of experimental results obtained by physical and numerical modeling (Figure 3). They were used in this research and called "experimental coefficients" (Table 2). Moreover, several analytical formulations have been published to obtain an approximate value of the coefficients *a* and *b*. In this work, that proposed by Ergun and Orning (1949) was used (Eq. 2) to obtain the "analytical coefficients" (Table 2). All the scenarios modelled are summarized in Table 3.

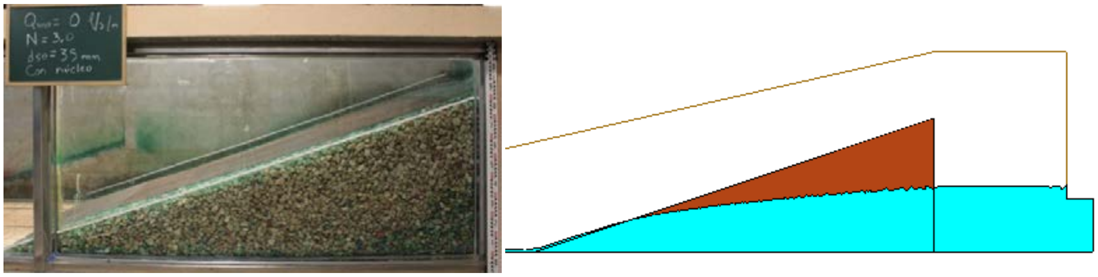

Figure 3. Example of physical and numerical models used by San Mauro et al. (2015) for the experimental assessment of *a* and *b*.

$$i = 150 \cdot \frac{(1-n)^2}{n^3} \cdot \frac{\nu}{g \cdot d_{50}} \cdot v + 1.75 \cdot \frac{(1-n)}{n^3} \cdot \frac{\rho_w}{d_{50}} \cdot v^2 \qquad (2)$$

where i is the hydraulic gradient, n is the rockfill porosity, g is gravity acceleration, ν is the water dynamic viscosity, d_{50} is the average diameter of gravels, ρ_w is the water density and v is the seepage velocity.

Table 2. Coefficients *a* and *b* of the flow resistance parabolic expressions used.

	Experimental coefficients		Analytical coefficients	
d_{50}	*a*	*b*	*a*	*b*
12.6	1.29	93.65	0.49	121.20
35.0	0.19	50.22	0.06	43.58
45.5	-	-	0.04	33.56

Table 3. Test Matrix.

Scenario	d_{50}	Slope *(N)*	Flow resistance expression
1	12.6	1.5	Experimental
2		2.0	
3		2.5	
4		3.0	
5	12.6	1.5	Analytical
6		2.0	
7		2.5	
8		3.0	
9	35.0	1.5	Experimental
10		2.0	
11		2.5	
12		3.0	
13	35.0	1.5	Analytical
14		2.0	
15		2.5	
16		3.0	
17	45.5	1.5	Analytical
18		2.0	
19		2.5	
20		3.0	

2.3. Safety Factor Against Mass Sliding

The formulation proposed by Toledo (1997) (Eq. 3) was taken as a starting point to study the stability against mass sliding. It allows to calculate a safety factor from a slice of a saturated porous material, based on the balance of forces (Figure 4).

$$F = \frac{1}{\gamma_{e,sat}} \cdot \left(\gamma_{e,sat} - \frac{\beta \cdot \gamma_w}{\cos \alpha^2}\right) \cdot \frac{Tan\ (\emptyset)}{Tan\ (\alpha)} \tag{3}$$

where F represents the safety factor against mass sliding, $\gamma_{e,sat}$ is the saturated specific weight, β is the uplift pressure coefficient *(if* $N \epsilon [1.5,2]$, β=-0.32N^2-1.52N-0.77; if N>2, β=1), α is the angle between the horizontal direction and the slope, and ϕ is the friction angle and N is the slope.

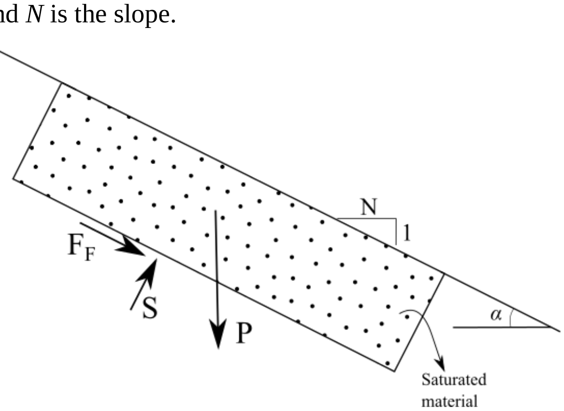

Figure 4. Balance of forces on a saturated slice proposed by Toledo (1997) to obtain a safety factor against mass sliding, where F_F is the friction force, S is the uplift force, P is the weight of the saturated material, N is the slope and α is the angle between the horizontal direction and the slope.

Equation 3 was adapted by adding two new forces on the slice (Figure 5): the weight of the dry layer above the water free surface (P_d) and the weight of the wedge shaped blocks (P_b).

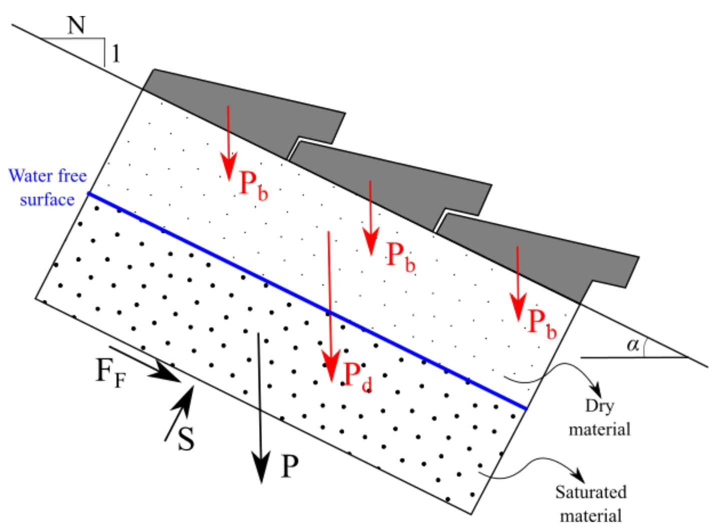

Figure 5. New balance of forces to obtain a safety factor against mass sliding of the drainage layer of WSB protections, where F_F is the friction force, S the uplift force, P the weight of the saturated material, N the slope and α is the angle between the horizontal direction and the slope, P_d is the weight of the dry material and P_b is the weight of the wedge shaped blocks above the drainage layer.

This results in a modified expression, specific for computing the safety factor against mass sliding for the drainage layer of WSB protections (Eq. 4):

$$F = \left(1 - \frac{\frac{\beta \cdot \gamma_W}{\cos\alpha^2}}{\gamma_{e,sat} + \left(\gamma_{e,dry} \cdot \left(\frac{1}{S} - 1\right)\right) + \left(\frac{P_B / S_B}{e_t \cdot S}\right)}\right) \cdot \frac{Tan\,(\emptyset)}{Tan\,(\alpha)} \quad (4)$$

where F represents the safety factor against mass sliding, $\gamma_{e,sat}$ is the saturated specific weight, β is the uplift pressure coefficient proposed by Toledo (1997), α is the angle between the horizontal direction and the slope, ϕ is the rockfill internal friction angle, e_t is the total thickness of the drainage layer, $S=e_{sat}/e_t$ is the saturated percentage of the total thickness of the drainage layer, P_B is the weight of the block, and S_B is the bottom surface of the block.

Since e_{sat} and S depend on both the material properties and the drainage flow, they must be obtained by means of physical or numerical tests. We chose the second option: e_{sat} was computed via numerical simulation for each combination of e_t and incoming flow.

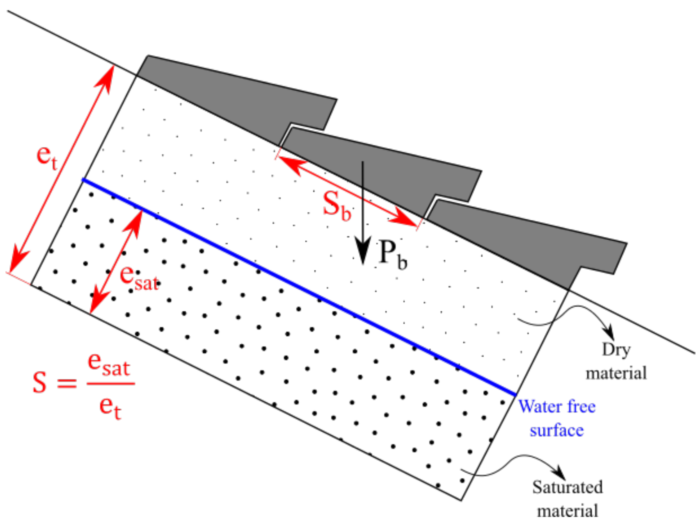

Figure 6. Scheme of the geometrical parameters required to calculate the safety factor against mass sliding of the drainage layer of WSB protections.

In this research, the drainage layer safety factor F was obtained for three values of e_t (10 cm, 20 cm, and 30 cm) that are reasonable from a construction perspective, and for four values of S (25%, 50%, 75% and 100%). Figure 8 shows an example of the plots resulting from the application of the proposed expression for each combination of N and e_t.

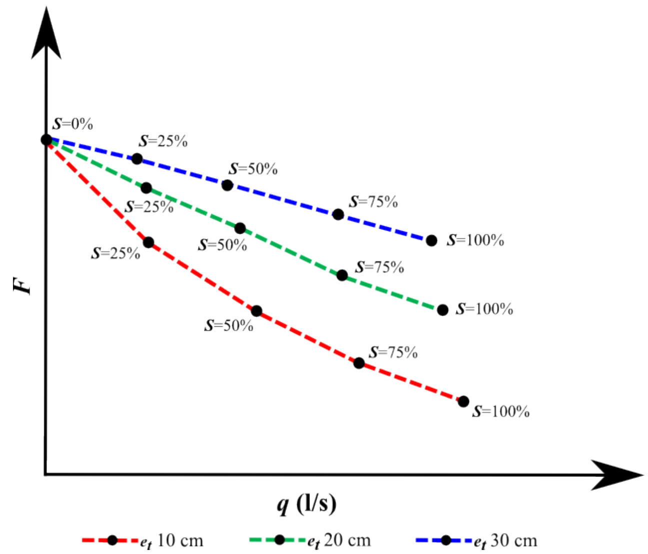

Figure 8. Scheme of a typical graph of the results obtained from a fixed slope (N) and variable thickness (e_t).

Two homothetic types of wedge shaped blocks were considered in this work in order to study the effect on the stability of a drainage layer: that used in the spillway of Barriga Dam (111 kg) and the block patented by Armorwedge (22.7 kg) (Morán and Toledo, 2015).

3. RESULTS AND DISCUSSION

3.1. Effect of Flow Resistance Expressions

Figure 9 shows the safety factor (F) obtained from analytical and experimental flow resistance expressions (Table 2), for two materials (M1 and M2), four slopes (N) and three thicknesses of drainage layer (e_t). The results show that the flow resistance expression adopted has a negligible impact on the values of F for the material M1. By contrast, the impact on F for the material M2 is more important, though moderate (less than 4% of discrepancy).

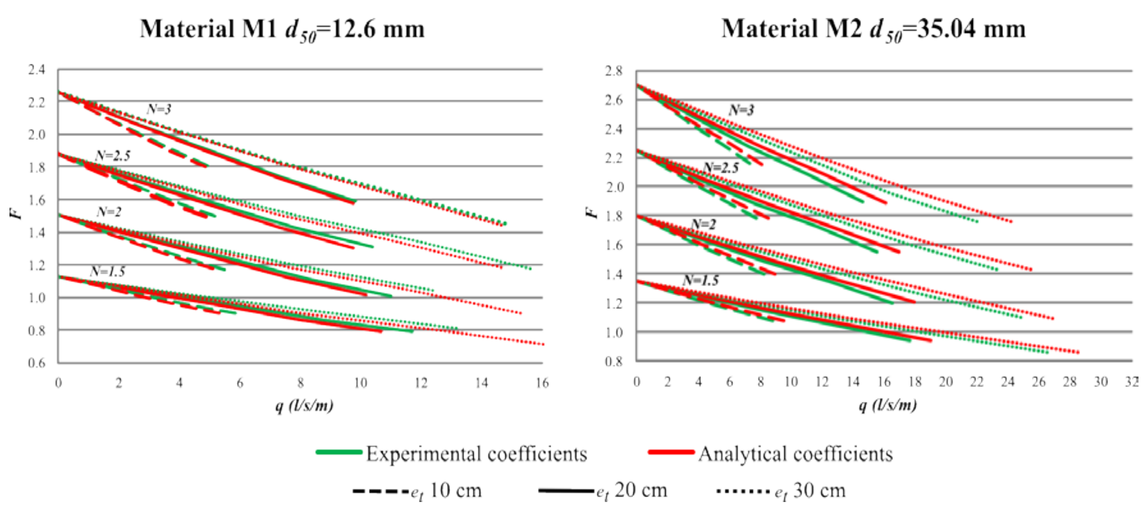

Figure 9. Comparison of safety factor obtained from different flow resistance coefficients (analytical and experimental). Weight of block: 111 kg.

3.2. Effect of Weight of Blocks

Figure 10 compares the safety factor F under two homothetic types of wedge shaped blocks (weights: 111 and 22.7 kg). The analytical flow resistance expression was adopted for this parametric study.

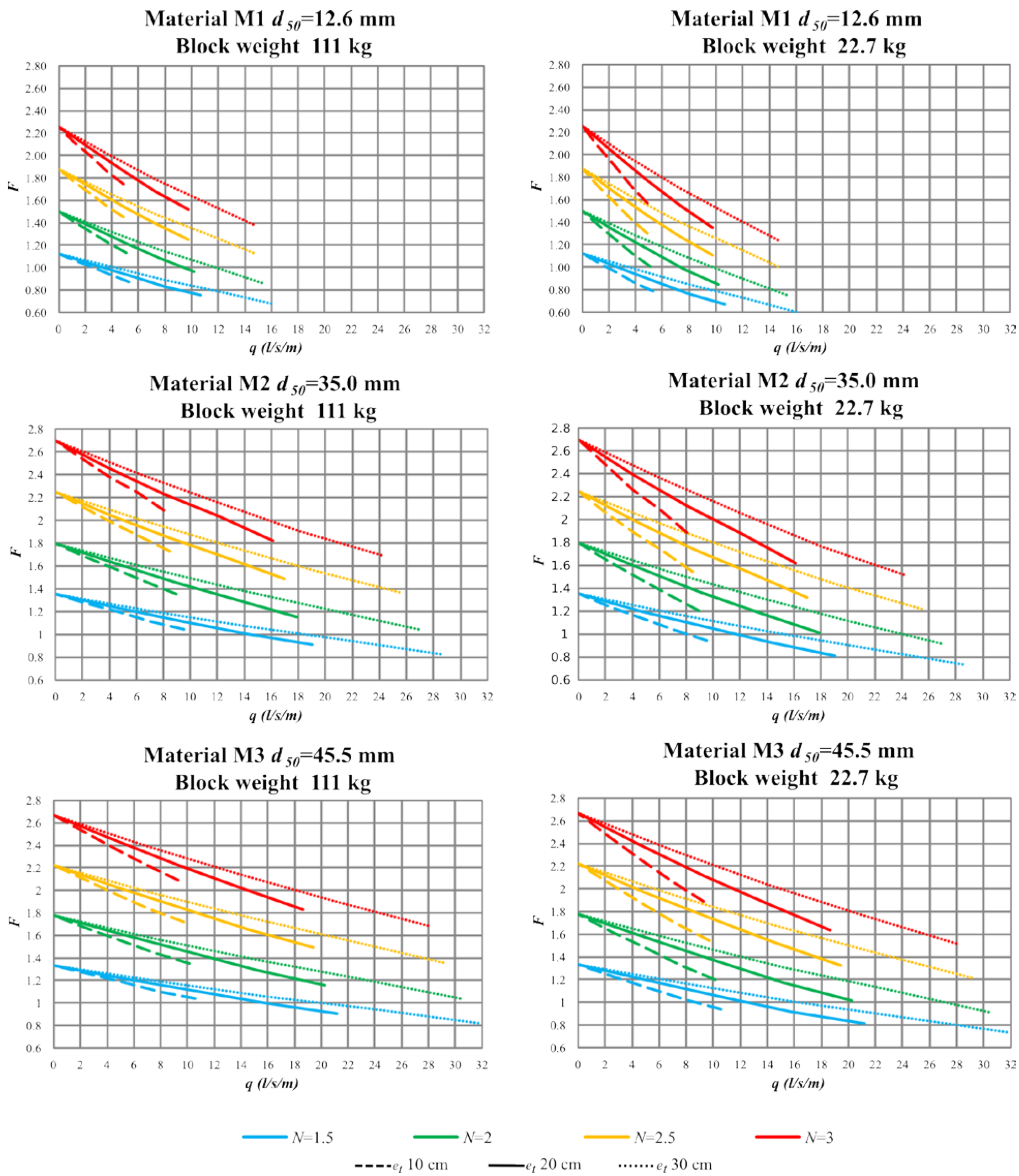

Figure 10. Comparison of safety factor obtained for different wedge shape blocks.

The following conclusions can be derived:

- A given design of the drainage layer is more stable with the heavier block.
- Wider drainage layers are more stable.
- Flatter slopes are more stable, although the value of F decreases faster, which means that the flow range between S=0% and S=100% is narrower.
- Material M3 is more stable than material M2, which in turn is more stable than material M1.

4. CONCLUSIONS

The main conclusions of this research are:

- The coefficients a and b of the flow resistance expression have a minor relevance in the safety factor F.
- For a given thickness of the drainage layer, increasing flows favor instability.
- An increase of thickness of the drainage layer results in increasing stability for a given leak flow.
- Heavier blocks increase the safety factor against mass sliding of the drainage layer.
- Flatter slopes are more stable.
- Coarser materials are more stable, though the correct placement of the blocks on the drainage layer could be hampered by an excessive size of the stones.

As a final result, we obtained graphs which relate the safety factor against mass sliding with the free flow capacity of the drainage layer. They can be used for preliminary design of the drainage layer of a WSB spillway, based on an estimate of the maximum expected drainage flow. Future research will focus on the calculation of the drainage flow.

5. ACKNOWLEDGMENTS

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