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THEORETICAL AND EXPERIMENTAL STUDY ON THE FLEXIBLE BARRIER OPTIMIZATION AGAINST DEBRIS FLOW RISK

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ABSTRACT

The topic of this study is the design of flexible fences to mitigate the risk due to debris flow phenomena by means of theoretical and experimental studies analysed in framework of the Rock Engineering System (RES).

The study of the interaction between debris flows and flexible barriers is a major challenge since many different aspects concerning both the slope characteristics and the structure features are involved. Debris flows are often triggered by the mobilization of debris deposits that are generated by rock fall of adjacent rock walls. The rock debris deposits are difficult to be characterized by the physical and mechanical point of view due to their large variability in volume distribution and, moreover, when dealing with high mountains environment, they are also strongly affected by the presence of water at different phases (solid or liquid) depending on the temperature. The debris deposit turns unstable in relation with the geotechnical and environmental features of the areas and the instability evolution in high mountain steep valley is often a debris flow. Debris flow destructive potential is very high and protections are often needed to reduce the debris flow risk.

This complexity determines the needs of comprehensive study able to include the global basin dynamic and the environmental conditions. An a-priori analysis of the influence of the different aspects can be useful to focus on the real driving aspects of the problem. Due to the complexity of the system the application of the RES methodology is recommended in order to clearly define the different assumptions needed, their influence on the simulations and a comparison among them.

RES allows investigating triggering criteria, flow and depositional processes and interaction of flows with protection fences in a rational way. For this purpose, an interaction matrix is created: it summarizes the key geotechnical parameters that influence debris flows, their interactions and debris/engineering protection opera behaviour. The goal is to quantify the diagonal-off terms to assess the residual risk after barrier construction, using back analysis from real debris flow event and data collection from literature.

This methodology is applied to analyze a debris flow event in the Italian Western Alps where numerical analyses are carried on to assess flow characteristics to be used for fence design through the application of an analytical and numerical model developed by the authors (Brighenti et al, 2013). In particular, the velocity and deposition heights have been estimated using the numerical code RASH3D (Pirulli, 2010), which is a single-phase model based on depth-averaged Saint Venant equations. Pathways of different lengths are studied to assess the input data necessary to design the protection barrier and to determine the associated risk. Simulation of the barrier at different places along the valley will also allow to determine optimal barrier location in terms of minimum residual risks by comparing the velocity, the volume and the energy of the debris after the barrier impact.

The work will produce a possible design scheme to be adopted in this environment.

KEYWORDS

Debris flow, flexible barrier, risk analysis, Rock Engineering System

INTRODUCTION

Debris flows occur when masses of loosed and saturated debris are mobilized along a steep slope under the effect of gravity. Their high flow velocity and interaction between the fluid and the solid component, combined with poor temporal predictability, cause debris flows to be one of the most hazardous and destructive landslide phenomena.

The need to protect infrastructures and residential areas has encouraged the development of numerous protection fences; reinforced concrete rigid barrier and earth structures are often used to reduce risk to an acceptable level. These types of barrier require high construction costs and an appropriate network of infrastructures to ensure accessibility during construction and maintenance phases.

Since the nineties, flexible barriers, composed by steel cables and ring net, have been employed. High deformability allows to absorb impact energy and to reduce process mobilization; furthermore, the net allows the water drainage and consequently, an elevate pressure reduction.

These barriers are designed using rock fall criteria, field in which there are more experimental experiences.

This research focuses on the analysis of the parameters that influence the flexible barriers design using the Rock Engineering System (RES). These parameters will be used to develop and to improve the numerical method proposed by Brighenti at al. (2013) to design cable-like retention barriers (Ferrero et al., 2015).

The approach to an engineering problem needs to identify parameters and variables that affect the project. In particular, we should provide answers to the following questions: could the parameter influence other parameters or the complete system? Could the parameter be influenced by external variables? A deep study is required to investigate the relationships between different parameters and to understand their interaction within the project.

The best approach to answer these questions is Rock Engineering System (RES) proposed by Hudson J.A. (1992). This methodology has been developed to overtake the limits represent by a “synthetic model” in aid of an “analytical model”. “Synthetic model” is a mathematical model that is built up from the component and has an unknown boundary of applicability; “analytical model”, instead, analyzes the whole of the rock mass and its characteristics.

A “bottom-up” approach, as the synthetic one, is too complicated and, generally, will not converge to the correct model. Furthermore, synthetic model procedure does not ensure that all the links are present: indeed, the omission of a critical component could completely invalidated the model.

RES has been used to analyze many rock mass engineering problems: in this article it will be applied to alpine channelized debris flows.

Interaction matrix

The relevant parameters that influenced the phenomenon, their mutual interaction and the combined behaviour of engineering structure and rock mass is easily depicted using the interaction matrix.

The relevant parameters are placed along the leading diagonal (diagonal terms, Pi); the influence of the parameter on the other is located at the correspondent intersection (off-diagonal terms) between the diagonals term.

The principal parameters are organized in a hierarchy, following a specific disposition: first the parameters linked to the rock mass, then those related to in situ conditions and finally the engineering project terms.

If a numerical value is attributed at the off-diagonal terms, the interaction matrix becomes a computation matrix and it's possible to define numerically the parameter dominance and to represent graphically the cause/effect relationship.

There are qualitative and quantitative code methods: the most famous and largely used (Harrison J.P et al, 2006) is the ESQ method (Expert Semi-Quantitative) which introduces a rating from 0 to 4, corresponding to no interaction, mild interaction, media interaction and critical interaction. The intrinsic risk can be identified by pathways that link the off-diagonal terms and it can be assessed as the product of these terms.

Interaction matrix application at debris flows phenomena

The interaction matrix proposed by the Authors, shown in Figure 1, allows to determine debris flow-flexible barrier behaviour. It's necessary to underline that this matrix refers to alpine debris flows which are caused by snow melting with consequent shear stress reduction.

The matrix is composed by six main parameters: rock conditions and basin lithology (P1), debris (P2), morphometry (P3), external agents (P4) and protection/prevention structures (P5). The first two parameters concern the rock mass characteristics, which condition both nature and volume of the debris; morphometry and external agents identify the situ conditions and barrier represents the interaction between the engineering project and natural phenomenon.

ROCK CONDITIONS AND BASIN LITHOLOGY	Debris volume and aereal extension are direct consequence of the rock mass weathering (**magnitude**)	Lithology influences the channel shape and entrainment of material	No direct effects	Anchoring and barrier foundations are conditioned by rock conditions and basin lithology
Debris acts as a protective layer	**DEBRIS**	Local change of slope characteristics (**unstability conditions**)	No direct effects	The structure have to be designed considerig the debris flow magnitude (**retention volume**)
Steep slopes could cause failures	Slope and basin shape define the potentially unstable volume (**magnitude**)	**MORPHOMETRY (slope and channel shape)**	Superficial basin hydrography is conditioned by slope (runoff)	Structure **location** in the basin and consequent resistance at the **impact energy**
Rock mass weathering / permeability decrease/ water pressure increases in the rock mass joints	**Rain**: pore pressure increase, liquefation phenomena, transition from hyperconcentrated flow to debris flow - **cohesion increases/decreases** under the effect of freeze/snow melting	Atmospheric agent changes the channel profile (superficial erosion, landslide)	**EXTERNAL AGENTS ("time bomb ")**	**Recurrence**
No direct effects	Barrier changes debris mechanical properties	The progressive barrier filling changes the channel shape (**maintenance**)	No direct effects	**PROTECTION/ PREVENTION STRUCTURES**

Figure 1. 5x5 interaction matrix applied to alpine debris flows

A modified ESQ code, with value from 1 (no direct effects) to 5 (high effects), is used to evaluate the risk associated to mutual interactions of off-diagonal terms as reported in Figure 2.

P1	5	3	1	3
2	**P2**	4	1	4
2	5	**P3**	4	5
3	5	2	**P4**	4
1	3	4	1	**P5**

Figure 2. Off-diagonal terms qualitative analysis using ESQ method.

The interaction matrix can be considered as a cause-effect diagram (C-E). Indeed, the influence that the parameter Pi has on the whole system, is represented by the i-th row of the matrix; conversely, the i-th column represents the influence of the system on the parameter Pi.

The Figure 3 shows the main parameters distribution on the cause-effect diagram (C-E). It's possible to note that debris (P2) and morphometry (P3) are the most interactive parameters and, on the other hand, the rock mass conditions and lithology are the least interactive. External agents (P4) are the most dominant and, consequently, debris and barrier are the most subordinate parameters..

This is also confirmed by the analysis of the possible pathways that link these parameters: if we consider the maximum value for the pathways of length between 1 and 5, it's easy to prove that morphometry, external agents and debris, in relation to the construction of a flexible barrier, have to be analyzed in detail.

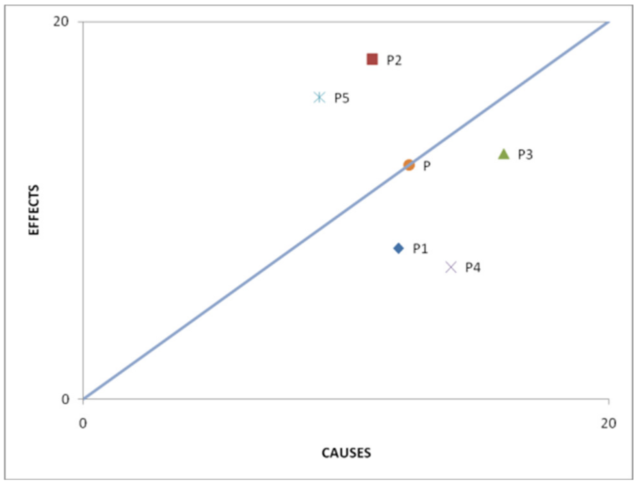


Figure 3. Cause-Effect diagram and associated main parameters distribution.

APPLICATION OF THE RES METHOD TO ANALYZE A SITE SUSCEPTIBLE TO DEBRIS FLOWS

RES method allows to study the complex phenomenon of channelized debris flow, considering all the possible parameter interactions and evaluating which are the most critical. From a detailed investigation of the pathways with the highest intensity values, it's possible to obtain a conceptual scheme for a safe design of protection barriers. Indeed, analyzing the interaction matrix we can highlight as the debris and morphometry considerably influence the barrier design especially in terms of mobilized volumes and impact energies; on the other hand, the barrier construction modifies basin profile and it generates new and potentially unstable accumulation area. Following the previous considerations, the Authors suggest simple guidelines and related methodologies to be adopted for the planning of protection structures in alpine environment.

For these reasons, the RES has been applied to the study of debris flow occurred in the basin of the Pellaud river, located in Rhemes-Notre-Dame municipality (AO); in this basin, especially in the spring season, rock detachments cause an accumulation of debris along the slope (P1-P2 interaction).

Snow melting (interaction P4-P2) causes the debris instability and debris flows with volume between 5000 and 15000 m3 occur. In this study, the description of the possible kinematic mechanisms, the unstable volume and the flow propagation have been taken into account using the numerical code RASH3D (Pirulli, 2010). Furthermore, starting from the velocity values and depositional heights obtained from RASH3D, the analytical/numerical method proposed by Brighenti et al., 2013 has been applied to design flexible barriers.

The RASH3D code

The RASH3D code allows to analyze the debris flow propagation in basins with complex topography. It is based on a continuum mechanics approach; in other words, the heterogeneous mass is considered as an equivalent fluid, whose rheological properties have to approximate the behaviour of the real mixture. Assuming that the flow height is much smaller than its characteristic length, the code integrates the balance equations in depth (Savage e Hutter, 1989) obtaining:

$$\begin{cases} \dfrac{\partial h}{\partial t}+\dfrac{\partial(\overline{v}_x h)}{\partial x}+\dfrac{\partial(\overline{v}_y h)}{\partial y}=0 \\ \rho\left(\dfrac{\partial(\overline{v}_x h)}{\partial t}+\dfrac{\partial(\overline{v_x^2} h)}{\partial x}+\dfrac{\partial(\overline{v_x v_y} h)}{\partial y}\right)=-\dfrac{\partial(\overline{\sigma_{xx}} h)}{\partial x}-\tau_{zx}+\rho g_x h \\ \rho\left(\dfrac{\partial(\overline{v}_y h)}{\partial t}+\dfrac{\partial(\overline{v_y v_x} h)}{\partial x}+\dfrac{\partial(\overline{v_y^2} h)}{\partial y}\right)=-\dfrac{\partial(\overline{\sigma_{yy}} h)}{\partial y}-\tau_{zy}+\rho g_y h \end{cases} \tag{1}$$

where $\overline{v}_x, \overline{v_y}$ are average flow velocity in the y- and x- directions, h is the flow height, τ_{zx} e τ_{zy} the shear resistance stress, $\overline{\sigma_{xx}}$ e $\overline{\sigma_{yy}}$ the depth-average stress, g_x e g_y the projections of the gravity vector.

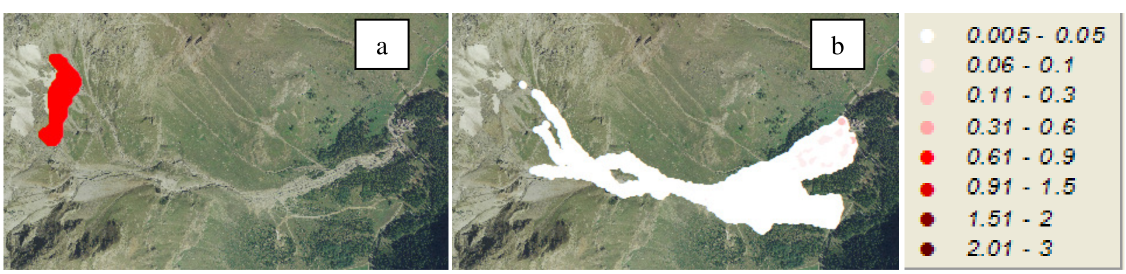
To carry out numerical analysis it is necessary to upload the pre-event digital terrain model (DTM), the geometry of the unstable volume and to introduce a rheological law.

The central point of the code and, generally, of these numerical methods, lies in the choice of the appropriate rheological law to describe the phenomenon: elementary rheology can imply rough mistakes; on the other hand, the calibration of a complex rheology, with many parameters, could be too hard. The code RASH3D implements two different rheologies: the frictional, in which the only parameter is the friction angle of the equivalent fluid (φ), and the Voellmy rheology, where in addition to the frictional component (μ) it is considered the effect of a turbulent component (ξ).

Parameters and rheological model

Using technical reports and available aerial photos a source area with volume of about 5000 m^3 has been identified (Figure 4a). The numerical analysis have shown that the Voellmy rheology best approximates the behaviour of past debris flows events, both in terms of deposition height and propagation distance, and it allows to take into account the non-rectilinear stretches of the T. Pellaud basin (Figure 4a), as well. Thus, the rheological parameters are: $\mu = 0.05$ and $\xi = 1000$ m / s^2 (Figure 4b).

In this first phase, we identified two significant values, the maximum velocity, vmax and the maximum flow height, h_{max} (Figures 4c and 4d), which allow to quantify the debris and morphometry effects on the barrier; h_{max} and v_{max} are the expression of the debris flow characteristics and these value indirectly contain information about volume, potential and impact energy. These two variables are the input values of the barrier design model proposed by Brighenti et al. (2013).



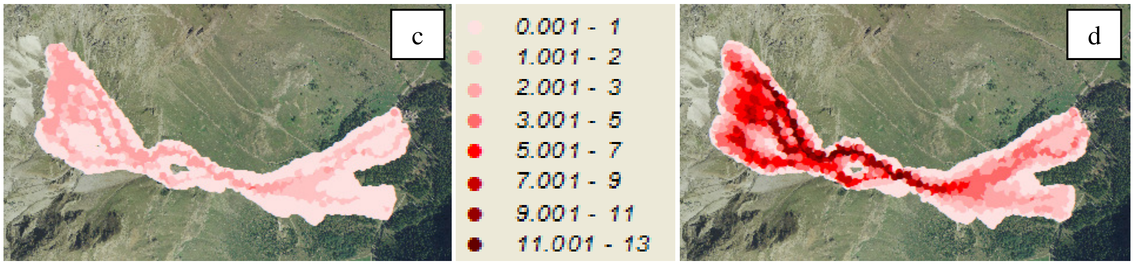


Figure 4. Identification of the potentially unstable volume (a). Results from the numerical analysis using RASH3D code: depositional heights (b) and maximum depositional heights (d). Maximum velocities at the end of the phenomenon (c).

Simplified analytical model to design flexible barriers

The model has been developed to design cable-like retention barrier against channelized debris flows. The impact pressure on the barrier can be determined as a sum of a dynamic and a static component (JSH Kwan, 2012). The dynamic component (Figure 5) due to the flow impact on the barrier, has the following equation:

$$q_d(x) = \alpha \cdot \rho_d \cdot v_0^2 \tag{2}$$

where α is an empirical coefficient that varies between 1.5 and 5 (Canelli et al., 2012; Ferrero et al., 2015), in this case assumed to be equal to 2, ρ is the flow density and v_0 the impact velocity.

With the filling of the barrier, the debris apply static pressure (Figure 5) equal to:

$$q_s(d) = k \cdot d(t) \cdot \rho_d \cdot g = k \cdot (h_0 + h(t) - z) \cdot \rho_d \cdot g \tag{3}$$

where k is the earth pressure coefficient, g is the acceleration of gravity, h_0 is the flow height, z is the vertical position under consideration and h(t) is the height of accumulated material at the generic time t. h(t) can be estimated as shown in equation (4):

$$h(t) = \sqrt{2 \cdot v_0 \cdot t \cdot h_0 \cdot tan\theta} \tag{4}$$

with θ the inclination of the slope behind the barrier.

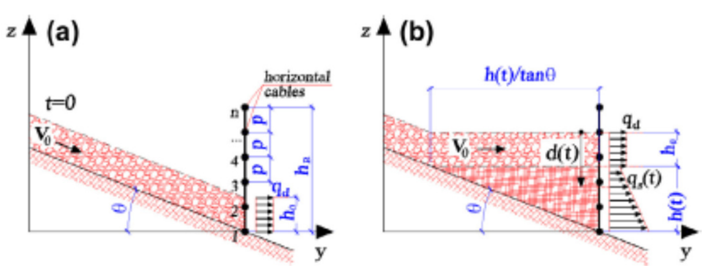


Figure 5. Debris accumulation behind the barrier and corresponding loads at a generic time instant (after Brighenti et al, 2013).

The barrier is schematized as a succession of n cable mounted at a constant distance p = hB / (n-1) with a constant load $q_i(z_i)$. Imposing a constant load along the cable is an acceptable simplification from the engineering safety point of view; this hypothesis allows to treat the problem as a two-dimensional one.

This model is based on the equation of equilibrium of a cable (Figure 6), fixed at the two ends and subjected to a horizontal load; it allows to derive the traction force components (H and T) and the maximum horizontal displacement ui (Figure 6a). The vertical forces transmitted by the connecting net to the single cable are neglected; only the horizontal cable deformation is considered.

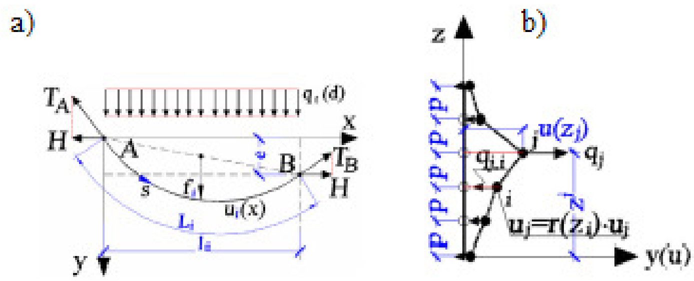


Figure 6. Scheme of a top view of a single cable under the constant load produced by the impact of a debris-flow (a); lateral view of the barrier and related displacement (b) (after Brighenti et al, 2013).

Flexible barrier design

Analyzing the trend of the flow in time (Figure 7), the construction of a debris flow net barrier is hypothesized. The barrier under consideration is characterized by a length of 20 m and a height of 5 m and it consists of 5 cables with a vertical distance p of 1.25 m, section of 0.024 m^2 and elastic modulus, E, of 210 GPa, with brake system that are activated by tensile forces greater than 70 kPa and they can stretch up to 2 m.

Using height and flow velocity values, respectively equal to h0 = 0.26 m and v0 = 11.00 m/s, the maximum traction force acting on the cables and the maximum displacement are obtained (Figures 8a and 8b). Actually, the model provides many output data, such as the stretching brakes, the instantaneous load transferred from the flow to the barrier, the dissipated and the total energy not mentioned in this article (see Brighenti et al, 2013).

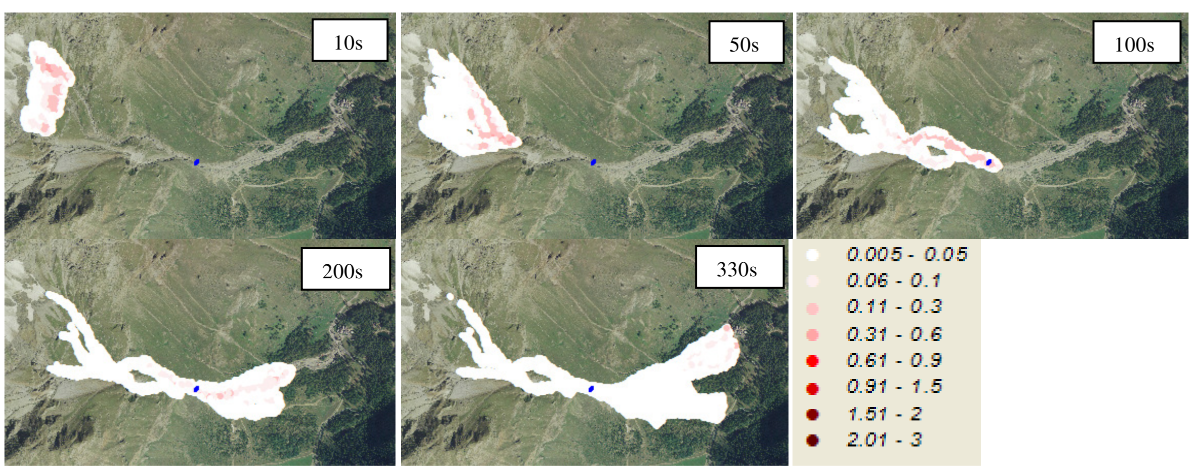
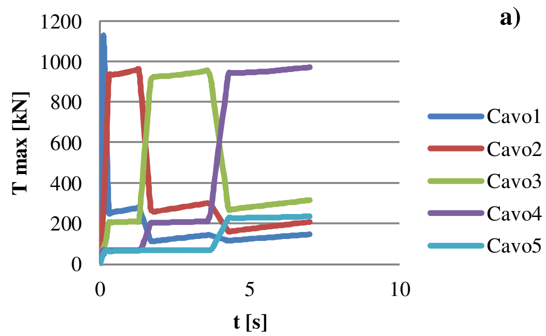


Figure7. Evolution of the flow phenomenon at successive time steps and positioning of the barrier (in blue).



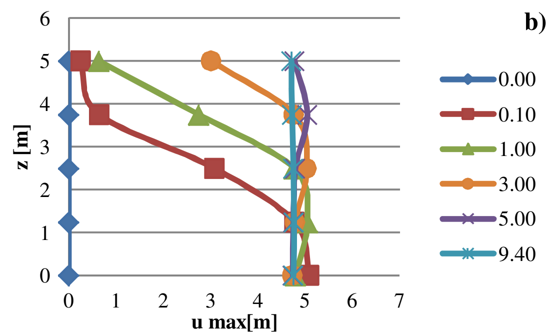


Figure 8. Trend of maximum tensile force acting on each cables (a). Maximum displacement of the barrier at different instants during the impact. (b).

CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper an accurate method to analyze the interaction between alpine debris flow and flexible barrier and to identify to the main parameters conditioning the protection structure-flow system is presented. For this reason, an interaction matrix, basic tool of Rock Engineering System (RES), is proposed. RES is a very simple and immediate method and it is a powerful tool for the identification of the interaction pathways with an high risk value.

The RES application at the site study of the Pellaud River (AO), has allowed to highlight that morphometry and debris volume, associated with the shear stress reduction caused by snow melting, greatly influence the design of a flexible barrier.

In this study, simple guidelines to design flexible barrier are provided. These guidelines require the application of the RASH3D code (Pirulli, 2010) to define the rheological parameters and the characteristics (depositional height and velocity) of the flow and, successively, the analytical-numerical model (Brighenti et al, 2013) to design cable like retention barrier.

Future developments will be aimed to obtain a coupled approach, because, nowadays, the numerical models have some limitations both in the simulation of the physical-mechanical behaviour of the flow and in the description of the dynamics of the impact and the behaviour of the barrier.

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