Two Control Works to Counteract the Inception of Debris Avalanches

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Abstract. Debris avalanches develop along open slopes, with significant lateral spreading, bed entrainment and flow-like motion associated to large runout distances. Recent numerical methods enhanced the simulation of the inception and propagation mechanisms with reasonable computational times and accurate description of the main kinematic variables such as height and velocity of the mobilised volumes. In this paper, a Smooth Particle Hydrodynamic (SPH) approach is applied to the simulation of propagation scenarios of differently-triggered debris avalanches in presence of two types of engineered slopes. The first option is the installation of a series of baffles in different geometrical combinations; whereas, the second alternative is the implementation of non-erodible zones. Both intervention types are conceived for the hillslope areas, so that the inception of debris avalanche would be limited since the very early stages of the phenomenon. A frictional rheological model is used, and also the role of time-space variable pore water pressures is considered. The discussion of the numerical results focuses on the modifications in the landslide dynamics induced by the two control work options, aimed to discuss the feasibility of such types of interventions in steep slopes prone to debris avalanche triggering and propagation.

Keywords: Mitigation · Protection · Landslide · Flow · Modeling · Slope

1 Introduction

Debris avalanches are among the most insidious flow-like mass movements. Far from the largest-sized slope instability processes, they are very frequent and can be amplified in volume during the propagation by factors of 10–50 or more. Thus, they are challenging processes to be forecasted and properly treated for territory protection. Significant examples come from the loose unsaturated pyroclastic soils of Campania region, Italy, loess deposits of many Countries including China, United States and Northern Europe (Cuomo et al. 2014, 2016).

A debris avalanche is controlled by a series of distinct though connected mechanisms such as: (i) propagation as a frictional-type resistant mass, (ii) pore water pressure dissipation, (iii) entrainment from the ground surface, (iv) slowdown of the front of the flow, (v) lateral spreading of the material, (vi) uneven propagation patterns. Specifically, (i) as a mixture of mostly coarse-grained soils and water (eventually free to move outwards the landslide body), debris avalanches often resemble the behaviour

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of frictional type materials whose shear resistance at the base is directly proportional to the flow thickness, and in a more complex way to flow velocity. Regarding that, different formulations have been proposed including turbulence or energetic dissipation terms (Pastor et al. 2014). (ii) A mechanism capable to increase the base shear resistance is the dissipation of pore water pressure due to vertical consolidation. In a flow with small thickness compared to length – that is the classical application field of the shallow water theories and later derived formulations – the mechanism of pore pressure change is fundamental, and even more if the soil consolidation coefficient is high as in the case of coarse-grained materials. (iii) Combined to the previous mechanisms, the bed entrainment has been more and more investigated in recent times, and most of the research agrees on that the faster and the thicker the flow, the more is the entrained material. For channelized flows, the total amount and the local thickness of eroded material may reach thousands of cubic meters and some meters, respectively (Cascini et al. 2014). For unchannelized flows like debris avalanches, less impressive modifications of the ground surface are observed after failure. However, especially the entrainment at the front of the flow where the velocity are the highest, enhance two further mechanisms which follow in the text. (iv) The slowdown of the flow front, in fact, is much related to bed entrainment (and to pore pressure dissipation as well) and it has been individuated as one of the best explanations for the short mobility of those unconfined flows which propagate along very steep slopes and stop just at the toe. In this sense, this mechanism should be considered as beneficial for shortening the runout and reduce the potential damages to urban settlements. (v) On the other hand, the spreading of material lateral to the propagation path is a direct consequence of the reduction of the velocity at the front of the flow. This issue has been investigated by Cuomo et al. (2014, 2016) for different combinations of frictional materials, pore water pressures, consolidation factors and slope types. In all the cases, the lateral spreading of flows increase the susceptible areas and mostly depends on the landslide dynamics (in turn related to slope topography, triggered volume, and so on) combined to the capability of the flow to entrain material from the ground surface. (vi) Therefore, very complex propagation patterns often characterize the debris avalanches, which must be accurately simulated in the framework of the territory protection.

2 Rationale and Details of Two Mitigation Options

Rather than collecting the flowing material at the toe of the slope in huge storage basins, which are very expensive and often beyond the available economic resources, or to deviate the flows towards some designated collection areas, which are always difficult to find and hardly accepted by the populations, here two less impacting intervention types are proposed. Both types are conceived to be realized along the hazardous slopes in the proximity of the potential source areas of future debris avalanches. We are aware that the individuation of these source areas could be a difficult task, however, both deterministic approaches at local and regional scales and even more recent probabilistic-aided methods have been testing since some years. Thus, this paper will rely on the assumption to know the location and geometric features of the source areas, which however will be varied over a range of values. In addition, we will focus on a simplified slope scheme (Fig. 1) for the propagation analysis to make the results easy to understand and somehow extendable to real cases. The aims of the numerical modeling will be to assess the modifications in the landslide dynamics induced by the two control work options. Different cases will highlight the potential and the drawbacks of the different solutions proposed.

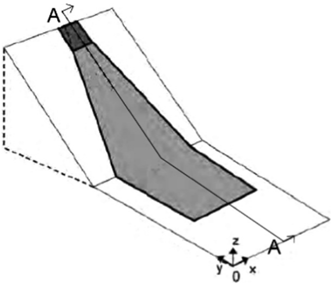

Fig. 1. Sketch of a simplified open slope prone to the inception of a debris avalanche

The first type of control work is an assembly of baffles, which are typically constructed as concrete quadrangular or prismatic pillars (equipped with pile foundations), capable to resist to the high impact and fast lateral flowing of mixtures of solid grains and water travelling at high velocity. We consider five baffles, organized in two lines at fixed relative distances, and we change the position along the slope and the presence of the baffles in the two lines. The second control work typology is the installation of two non-erodible bands at two differently designated locations.

The configurations here considered for both intervention types do not pretend to be exhaustive, but they are thought useful to outline some different behaviors of the flows when interacting with them.

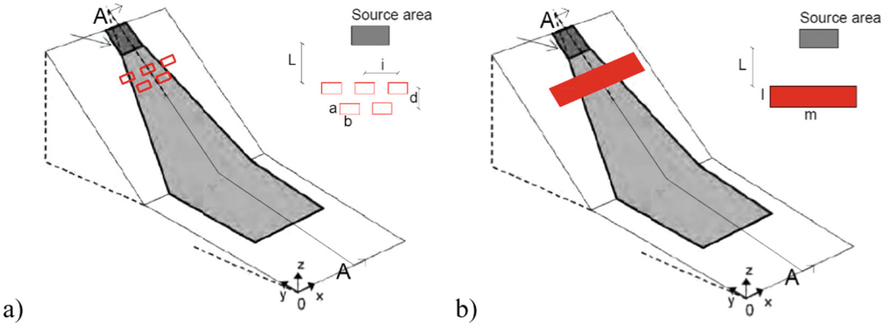

Fig. 2. Schematics of a slope engineered with: (a) artificial baffles constructed to counteract a debris avalanche; (b) non-erodible zone

3 Numerical Modelling

3.1 Materials and Methods

The model proposed by Pastor et al. (2014) was here used. It is based on the Smoothed Particle Hydrodynamics (SPH) method, and considers the landslide body as a mixture of a solid skeleton saturated by water. The pore water pressure is one fundamental variable of the model, and it may dissipate along the normal to the ground surface. Both the pore pressure and the solid skeleton velocity (the other fundamental variable) are computed as the sum of two components related to two separate processes: propagation and consolidation. More details and applications are available in Cuomo et al. (2014, 2016). It is worth noting that the governing equations are integrated along the vertical axis, so that the problem is solved through a 2D depth-integrated model, with the accuracy combined to a low computational time. During the motion, the landslide may entrain ground surface material, which has nil velocity and nil pore-water pressure. The cumulative eroded depth at any location depends on the landslide erosion rate, local slope angle, height and velocity of the landslide (Blanc et al. 2011) but also on the time span during which the landslide keeps propagating at that location.

The numerical simulations were performed for a schematic open slope, made of an upper steep hillslope and a lower flatter piedmont, inclined as i_1 and i_2, respectively (Fig. 1). The landslide volume was located at the top of the upper slope, and released to be able to flow and interact with two lines of baffles (Fig. 2a) or non-erodible zones (Fig. 2b). A detailed 1 m × 1 m Digital Terrain Model (DTM) was used, and the landslide mass was discretized by a set of 544 SPH points, 1 m spaced, with a uniform soil height of 1 m inside the source area. A frictional rheological model was used with the parameters taken from literature (tan ϕ_b: friction angle equal to 0.5, h_w^{rel}: height of water table relative to soil thickness equal to 0.4, p_w^{rel}: pore water pressure divided by soil liquefaction pressure equal to 0.5, B_{fact}: consolidation coefficient equal to 10^{-2} $m^2 s^{-1}$, K_r: entrainment coefficient equal to 0.03).

The two control work typologies were simulated as follows: (i) along the obstacle boundaries, the normal velocity of the flow was set to zero; (ii) inside the non-erodible zone, the landslide entrainment rate was switched to zero. Two series of numerical simulations were performed.

The first set of analyses was carried out to understand how the position of the obstacles, namely (a) in the upper, (b) middle or (c) terminal zone of the slope, can change the dynamics of the debris avalanche. Moreover, for the first case, a reverse position of the obstacles was analysed, with two obstacles in the first row impacted and three in the second one. Analogously, a non-erodible zone was allocated at one of the three previous locations, along a distance equal to that occupied by the baffles ($l = d + a$ and $m = 2i + b$ in Fig. 2). A second set of analyses was aimed to outline the role of both the interventions in the tempo-spatial evolution of the mobilized volume along the slope. In this regard, a sensitivity analysis was conducted changing both the slope inclination (30–40°) and the initial volume (500–15,000 m^3).

In both cases, the differences with the original slope were thoroughly discussed.

Table 1. List of debris avalanche cases considered for numerical simulation

Case	Slope angle, i_1 (°)	Volume, V (m^3)
1	30	500
2	30	5,000
3	30	10,000
4	30	15,000
5	35	500
6	35	5,000
7	35	10,000
8	35	15,000
9	40	500
10	40	5,000
11	40	10,000
12	40	15,000

3.2 Effects of Baffles

The configurations analyzed are reported in Fig. 3. Once released from the source area, the debris avalanche will be altered by the slope topography, and interacts with the ground surface along the travel path and with the baffles at the location where they are. After the deposition has occurred, some issues are worth of investigation such as the material entrained along the slope, the volume stopped behind the baffles, the maximum runout distance and the extent of the invaded zones.

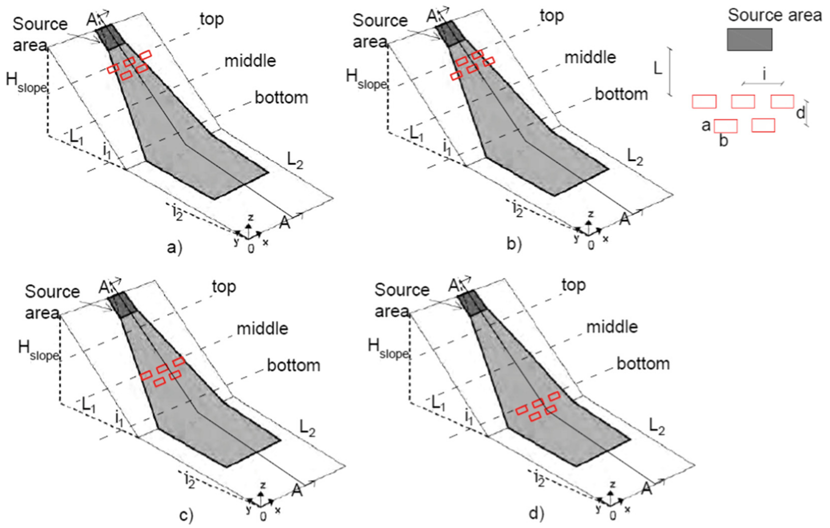

Fig. 3. The four computational schemes used in the SPH simulations (H_{slope} = 130 m, i_1 equal to 30°, 35° or 40°, a = 10 m, b = 5 m, d = 15 m, L equal to 30 m, 80 m or 130 m)

As depicted in Fig. 4, the installation of the baffles highly changes the eroded depths along the slope and the final deposition thicknesses and somehow the final runout. Regarding the former issue, it is worth noting that the debris avalanche entrains material at a nearly constant rate (Δz/x) in the upper part of the slope. Then, a drastic reduction of entrainment occurs at the baffle location, as expected. More interestingly, the debris avalanche starts to entrain material again downslope the baffles. However, material is entrained at a lower rate than after the interaction with the baffles. It means that the baffles completely modify the dynamics of landslide as desired. Of course, this drastic change would be positive in case the runout and deposition at the toe of the slope would be both reduced. Such expectations are confirmed in Fig. 4. The runout is decreased and some of the soil volume is trapped behind the barrier for any baffle combination.

More in general, the installation of baffles is beneficial as the total mobilized volume of any debris avalanche of Table 1 is reduced. It is simple to understand that the interaction of a debris avalanche with fixed obstacles reduces the overall kinetic energy of the landslide. Although some local increase of the landslide velocity may occur as, for instance, where the flow is constrained to pass among the baffles; then, the overall effect is that less volume continues propagating downslope because some parts of the landslide volume are stopped behind and nearby the baffles.

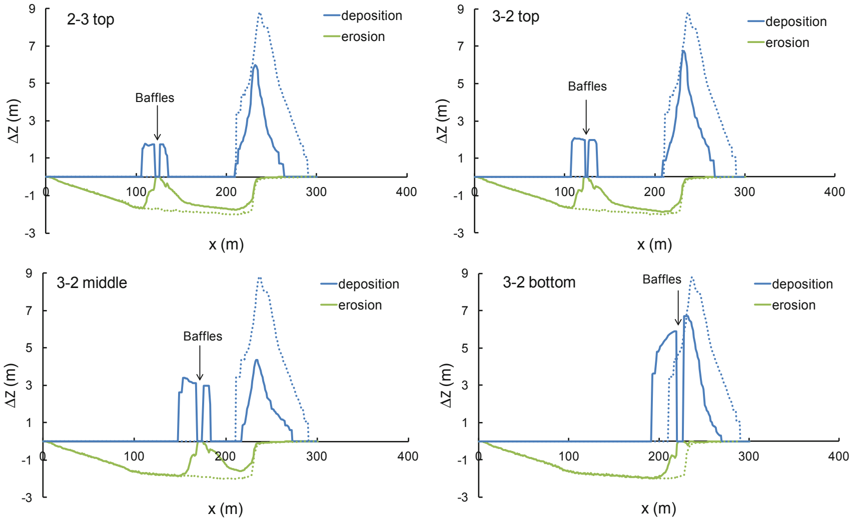

Fig. 4. Simulated eroded thickness (negative values) and deposition heights (positive values) along the slope x-coordinate for different arrangements of baffles, compared to the original slope (dashed lines)

For engineering purposes, it is useful to outline the reduction of the mobilized soil volume in the slope equipped with baffles, compared to the natural slope. Figure 5 shows a positive effect of the baffles in all the cases of Table 1. In general, the reduction in volume is higher than 25%, as the slope angle of the line quite well interpolating ($R^2 = 0.9798$) the plot of Fig. 5 is equal to 0.7366.

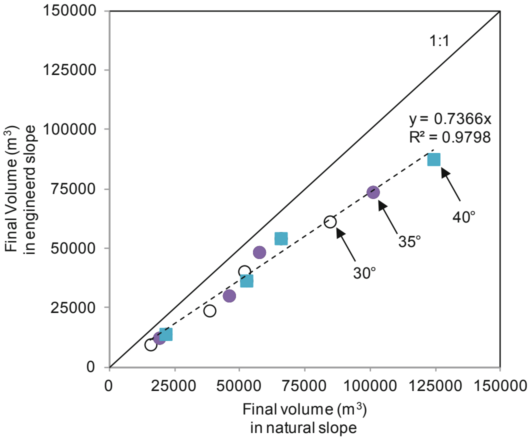

Fig. 5. Positive effect of baffles on the reduction of volume amplification during the propagation

3.3 Effects of Erosion Control Zones

The alternative countermeasure based on the use of the non-erodible zones is analyzed the same way of the baffles. Three relevant combinations are proposed for the numerical simulations, as those depicted in Fig. 6. In all the cases, inside a non-erodible zone, long as the distance from the uppermost baffle to the lowermost one, the prevention of entrainment is guaranteed. On the other hand, the overall benefit and the eventual side effects are here evaluated through the numerical modeling.

Differently from the baffles, the erosion control has major local effect and modest general consequence on the landslide. Figure 7 outlines that the entrainment rate ($\Delta z/x$) is almost the same upslope and downslope the erosion control areas. It means that the landslide dynamic is poorly modified. This is observed in all the combinations (Figs. 6 and 7). Based on that, one can say that the benefit of this countermeasure direct depends on the extent of the non-erodible areas, the larger the better, as the volume reduction relates exclusively to the extent of the treated area. Of course, the closer the intervention is to the toe of the slope, the faster is the landslide when reaching the control work. This last observation would be not general but valid for the examined cases of relatively “short” slopes, long something like 300–400 meters. Figure 8 shows that the benefit in terms of volume reduction is negligible for small-medium sized landslides, and does not exceed the 18% for the biggest ones here considered, in both cases much less than the values relative to the baffles.

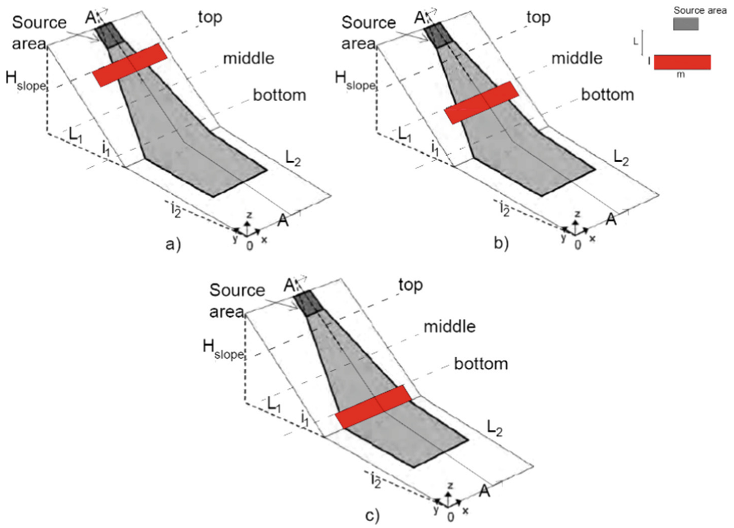

Fig. 6. The three computational schemes used in the SPH simulations

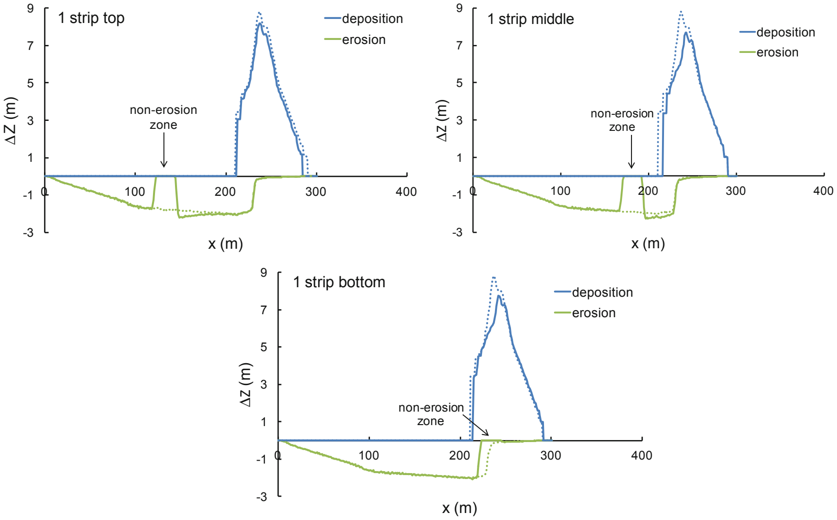

Fig. 7. Simulated eroded thickness (negative values) and deposition heights (positive values) along the slope x-coordinate for different erosion control options, compared to the original slope (dashed lines)

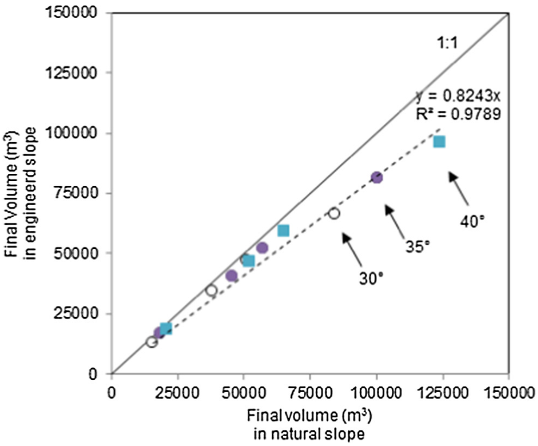

Fig. 8. Reduction of the total mobilized volume due to the erosion control options in comparison to the landslide evolution along the natural slope

3.4 Discussion

The previous numerical analyses aimed to provide some insights on the performance of two types of interventions along a slope affected by the inception and propagation of a debris avalanche. Started from a relatively small area with an initial volume of 500–15,000 m^3, the debris avalanche may hugely increase its volume, with the twofold negative effect to (i) entrain material from the ground surface, so steepening those zones, and (ii) involve large areas due to lateral spreading of the landslide body mass. Both interventions proved capable to mitigate the landslide volume increase (Fig. 9). However, the mechanisms are completely different. In the case of baffles, the landslide velocity is somehow diminished due to the interaction of the landslide with the baffles, and this is evidenced by the change in the entrainment rate along the slope (Δz/x), as shown in Fig. 4. In the other case, the erosion is prevented in the specific location of the non-erodible areas but the landslide velocity is nearly unchanged, in fact the entrainment rate (Δz/x) does not change. Figure 9 provides an overall assessment of the landslide volume increase, which is exponential in both the natural and engineered slopes but with lower values in the case of non-erodible zones and even less for the baffles.

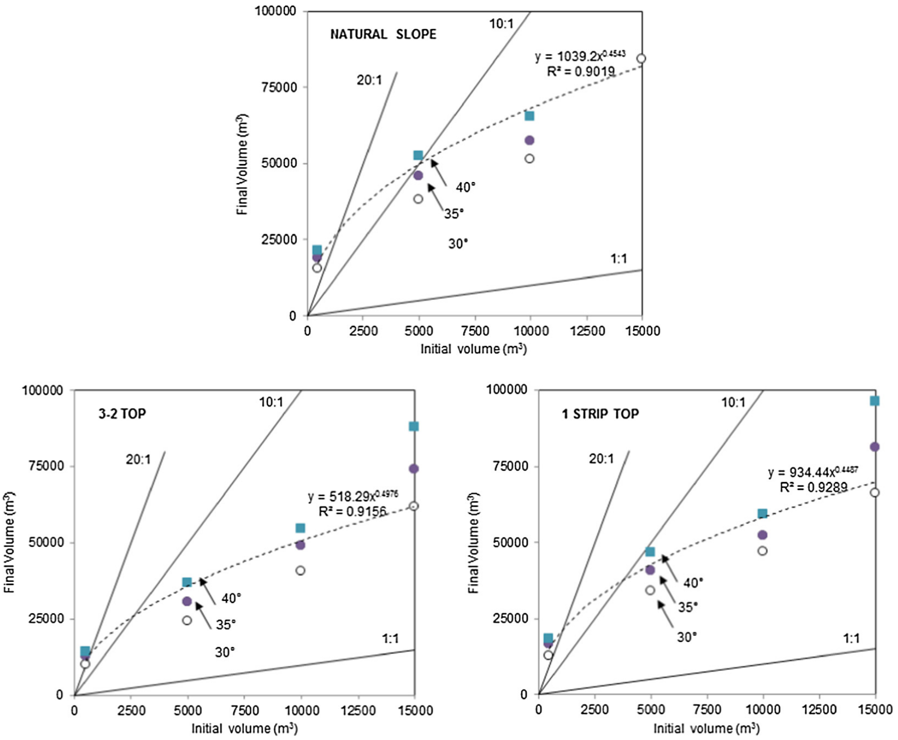

Fig. 9. Increase of the landslide volume due to bed entrainment in the natural slope or in the slope engineered with baffles (3-2 TOP) or erosion control intervention (1 STRIP TOP)

4 Conclusions

In the present study, a numerical analysis has been carried out to evaluate the change in the landslide dynamics related to the construction of baffle combinations or to the implementation of erosion control. In both cases, the beneficial effects have been outlined. Several issues, which may influence the final choice among these or other options for landslide intervention, were beyond the scope of this paper. Just to mention the possibility to effectively construct the baffles, the costs of their foundations, and the environmental impact, all issues which could limit the sustainability of such intervention. On the other hand, the erosion control option could be easier to implement and less environmental impacting, however its efficacy could be not enough high to ensure the desired safety target. Notwithstanding these limitations, the fundamental mechanisms associated to both the interventions were outlined, and also some practical evaluations of the orders of magnitude of the landslide entrainment were provided. Further research will allow to better focus and fine-tuning some issues which here were only preliminary analyzed.

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