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Improving three-dimensional rockfall trajectory simulation codes for assessing the efficiency of protective embankments

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Trajectory simulation codes are widely used for assessing and zoning rockfall hazards in view of land use planning. These tools may also be used to estimate the benefit in terms of risk reduction derived from the construction of protection structures such as embankments. This paper investigates the relevance of currently used trajectory analysis tools for this purpose through a real case study. The trajectory analysis is first used to assess the hazard and define the embankment geometry. In a second time, it is used to assess the embankment protection efficiency after its insertion in the digital terrain model. Results reveal abnormal trajectories in the vicinity of the embankment suggesting limitations related to both the spatial resolution of the terrain model and to the rebound models. To cope with these limitations, an innovative approach is proposed and evaluated for improving the ability of the simulation code in assessing the residual hazard down the embankment.

1. Introduction

In mountainous regions fragmental rockfall events are considered a major threat for human lives and infrastructures given their occurrence and in spite of their relatively reduced intensity (rock mass block volume up to few cubic meters). Rockfalls are also a significant hazard in open-pit mining and quarrying [1]. In this context, rockfall propagation simulation tools are used for land-use planning and protection purpose. Among the possible parades, protecting the elements at risks may involve civil engineering structures placed down the slope to stop or to deviate the rock blocks.

Rockfall trajectory simulation codes aim at evaluating the probability for a block detached from a given release zone to reach any point on the downhill slope by reproducing the possible trajectories. Different methods exist for simulating the propagation of a rock fragment [2], mainly differing by the way to model the mechanics associated to the block rebound [3]. The block rebound is governed by the mechanical interaction between the block and the slope surface which is generally modeled thanks to restitution coefficients correlating the impact velocity to the rebound velocity. These coefficients have most often been calibrated empirically, based on post-event analysis or tests in the lab [3,4].

Rockfall hazard was classically assessed using two-dimensional (2D) rockfall simulations. 2D approaches simulate the propagation

of the rocks through profiles corresponding to the preferential rockfall propagation paths as predefined based on an expert knowledge. Alternatively, three-dimensional (3D) simulations are now currently conducted. Such approaches consist in propagating the rocks through a digitalized surface of the site, called Digital Terrain Model (DTM). Both 2D and 3D approaches have been proved equally efficient in estimating the rock passing heights and rock velocities in a specific rockfall propagation zone [3]. 3D approaches do not require defining the preferential profiles, reducing the subjectivity of the study. These approaches naturally account for the complexity and variety of possible trajectories. The main drawback of 3D approaches is the amount of field surveyed data they require to be relevant.

Embankments are massive earthworks, most often constructed perpendicular to the slope with the aim of intercepting the blocks on their route down the element at risks [5,6]. Their mountain-side facing is steepened so as to prevent blocks from bouncing or rolling over the structure, with vertical batters typically less than 25°. The design of embankments consider the statistical distribution of the blocks passing heights and energies, as provided by the rockfall trajectory analysis, to first address their ability in controlling the blocks trajectories and, second, withstanding the impact [6]. The first facet of the design aims at determining the embankment height based on the block flying height.

Like for any protective structures, the embankment efficiency may be assessed based on the residual hazard, which is here defined as the hazard down the structure once completed. The residual hazard is evaluated based on the occurrence of rare to extremely rare events and its accuracy depends on the number

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of simulations. The height of a projected embankment may be determined in order to lower the hazard down to a targeted value.

To date, a very limited number of published paper deals with the use of trajectory analysis tools while in presence of an embankment in view of assessing the benefit of its construction in terms of hazard reduction. Only a few refer to studies conducted in such an aim, but with minimum details concerning the method and eventual problems encountered [7–9].

This paper addresses the issue of using trajectory analysis tools for assessing the efficiency of embankments in controlling the blocks trajectory. First, a commonly used trajectory analysis tool is used pragmatically on a case study with the aim of designing an embankment. The results allow highlighting two limits of the method: the validity of the restitution coefficients and the spatial resolution of the DTM. To overcome these limitations, an approach based on the coupling of two trajectory analysis tools with local models at the structure scale is proposed and the results obtained using this coupled approach are discussed.

2. Trajectory analysis of the case study

2.1. Methodology for rockfall hazard assessment

Rockfall hazard was assessed using the simulation code Rockyfor3D [10,11]. This 3D code propagates the block through a succession of free flights through the air and rebounds on the soil. The sliding of the rock is not accounted for and the rolling motion is modeled as a succession of short bounces. Rockyfor3D allows modeling the blocks trajectories based on a hybrid approach that consists in accounting for the blocks shape in a simplified manner during the impact phase. Such an approach constitutes a trade-off, in terms of impact modeling accuracy and computational duration, between the approaches (called rigid body approaches) integrating precisely the influence of the block shape in all phases of the trajectory and the lumped-mass approaches that do not account for the block shape [2].

This code propagates rocks through a DTM modeled as a raster map. A raster map can be seen as a matrix in which each cell

value represents the mean terrain elevation of the square cell. The terrain is therefore modeled as an assembly of vertical steps. The square cell size depends on the resolution of the raster map. In each cell, the soil surface is modeled as a facet with an orientation characterized by two angles: the aspect angle and the slope angle, the latter in the steepest slope direction. Both these values are classically calculated based on the elevation values in the neighboring cells [12]. The accuracy of the calculation of both the aspect and slope angles is thus strongly depending on the resolution of the DTM.

The rebound calculation is conducted in two independent phases, the first aiming at giving the deviation of the block trajectory after the rebound and the second aiming at giving the block rebound velocity [13]. The block trajectory deviation is estimated assuming that its incident trajectory (i.e. before the impact) is contained in a plane normal to the soil surface, referred to as the incident plane. Similarly, the block reflected trajectory (i.e. after the rebound) is contained in a so-called reflected plane, normal to the soil surface. The deviation angle δ^{re} is the angle between these two planes. It is sampled from a statistical distribution determined from experimental results [10]. The tangential, normal and rotational components of the rebound velocity V_t^{re} , V_n^{re} , ω^{re} are calculated from the components of the impact velocity V_t^{in} , V_n^{in} , ω^{in} using a model compiling recent advances in rocks rebound modeling from the literature [14]. However, the general approach for the calculation is based on the model developed by Pfeiffer and Bowen [15]. This modeling approach was shown to provide satisfying results at the slope scale [10,16].

The rockfall hazard level in each point of the site is related with the probability for a rock to reach this point. This is a simplified approach compared to the classical one considering both the occurrence of the event and its intensity [17]. This is relevant when considering a linear structure where a rockfall event corresponds to a rock impacting the structure.

Practically, the conversion into a rockfall hazard is confronted to the absence of consensus concerning the threshold values to consider in 3D approaches. The threshold values used to convert the probability for a rock to reach any point into a hazard level were developed for 2D approaches. The calculated rockfall hazard

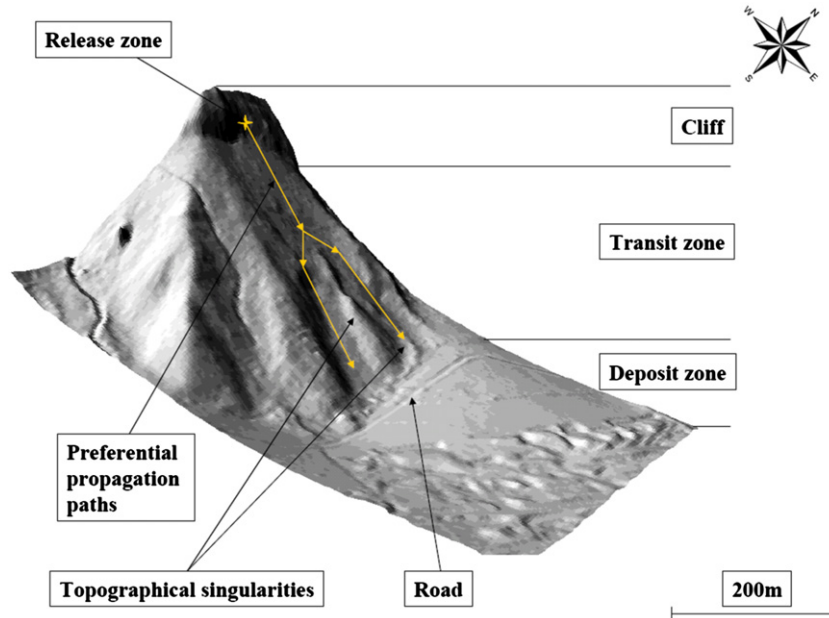


Fig. 1. 3D view of the study case site from Lidar data.

corresponds to the probability of a rock to pass through the elevation line defined on the topographical profile. These threshold values are not relevant for 3D approaches where the rockfall hazard is the probability for a rock to pass into a raster cell. Consequently, this value depends on the resolution of the DTM: the higher the resolution, the smaller the probability. This dependency to the resolution can be suppressed by expressing hazard values per unit area (that is per m^2) or per meter along a road.

2.2. Site description

The study case is adapted from a real site in the French Alps, exhibiting an average exposure to rockfall hazard. As it is used for illustration purpose, its precise location is deliberately not given. The topography of this site is presented Fig. 1, obtained from LIDAR data.

Three main areas can be identified: (a) the rockfall release area consists of a limestone cliff. A unique block detachment point is considered for this study, located approximately 260 m above the road. (b) A scree made of fine to coarse materials, with a slope angle locally ranging from 30° to 60° . (c) A lower slope angle area, typically 10° , consisting of agricultural zones crossed by the road to be protected. A village stands downhill this area.

Table 1
Soil characteristics.

	Rg70	Rg20	Rg10	Rn
Scree	0.2	0.1	0.05	0.42
Road	0.01	0.01	0.01	0.35
Agricultural terrain	0.01	0.02	0.05	0.21

Fig. 1 also exhibits two topographical singularities. The first one is oriented along the slope, and creates two preferential paths for the blocks propagation, hereafter referred to as south path and north path depending on their position with respect to the north. The second singularity is smaller and consists of a comma-shaped hill at the end of the north path. It is expected to deviate the blocks southwards.

The spatial resolution of the DTM has been fixed to 2 m in order to keep the duration of the simulations reasonable while having a rather precise description of the whole site topography. This resolution is consistent with engineering practices [9,18]. The block considered has a cubic shape, a $2 m^3$ volume and a $2500 kg/m^3$ unit mass. After detachment, the block freely falls over 20 m before touching the scree surface.

The mechanical properties of the surfaces involved in the block propagation are characterized thanks to the soil roughness, based on three classes ($Rg70$, $Rg20$, $Rg10$) and the normal restitution coefficient, Rn . Values considered for the three surfaces encountered on this site are presented in Table 1. The values of $Rg70$, $Rg20$, $Rg10$ and Rn have been determined following the methodology exposed in Rockyfor3D manual [19]. The agricultural terrain is characterized as a “fine soil material (depth > 1 m)”.

Five hundred thousand simulations were conducted resulting in the hazard map presented in Fig. 2. As mentioned in Section 2.1, the choice was made to relate rockfall hazard in each point of the site with the probability for a rock to reach this point. Consequently, the hazard is defined as the probability for a block to pass per unit area (that is per m^2) in each cell of a raster map or per meter along a road. The probability for a detached block to reach the road is as high as 88%. Some blocks stop near the first houses of the village. The vast majority of the blocks propagate in the North path (63% of the released blocks). The trajectories of these blocks exhibit a pronounced southwards deviation due to the comma-shaped singularity. Fig. 3 shows that the highest hazard along the

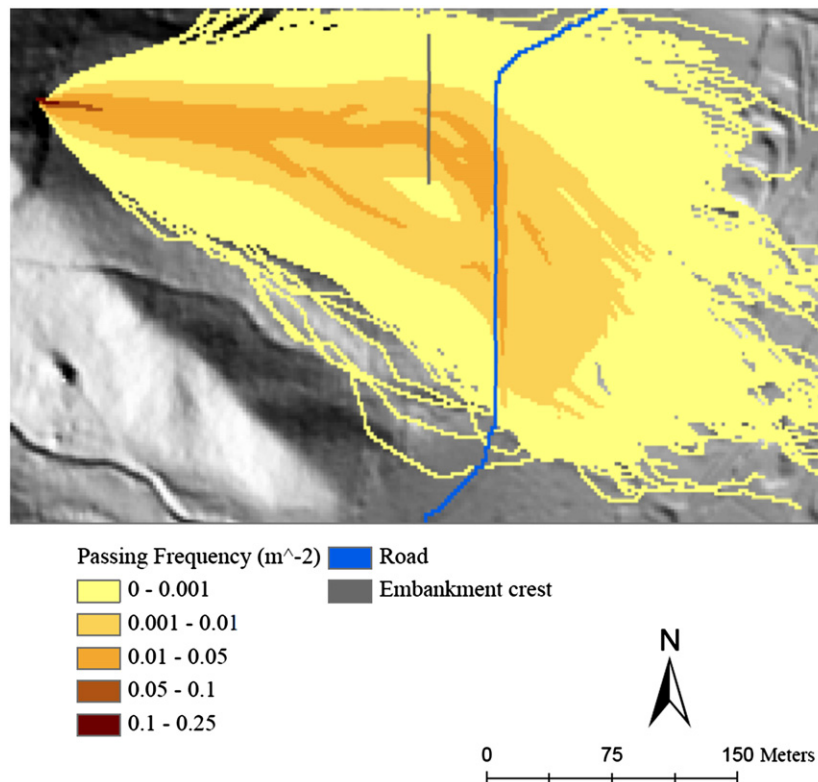


Fig. 2. Initial hazard map.

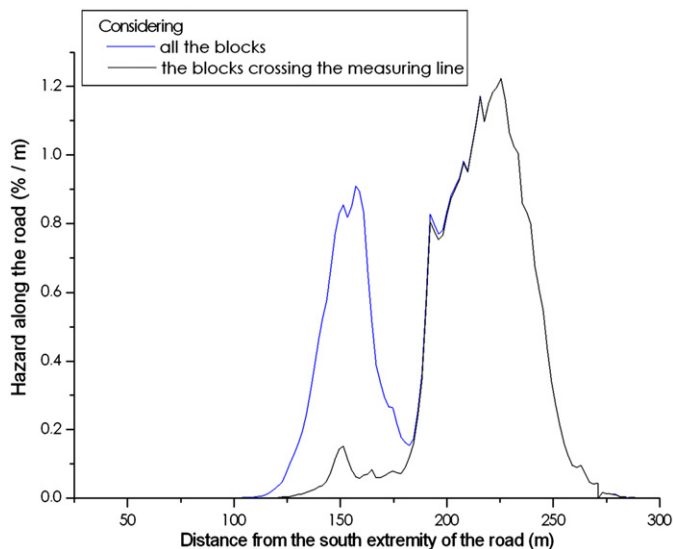


Fig. 3. Hazard along the road in terms of occurrence line per meter of road.

road results from these blocks with a maximum hazard value of 1.2% per meter of road.

Considering the peculiarity of the propagation scheme this study will mainly focus on the risk resulting from blocks propagating in the north path, without any consideration for the blocks passing in the south path. This limitation is motivated for demonstration purposes. Of course in a practical context the whole site hazard assessment would require considering all the trajectories. Thus, the embankment hereafter proposed aims at intercepting the blocks passing in this path, with a targeted residual hazard along the road of 0.1% per meter.

2.3. Embankment positioning

Classically, embankments are positioned uphill the elements at risks preferably where the passing height and energy of the blocks are minimum. The topography may also be considered. In this case, the embankment is planned to be built 50 m uphill the road, just before the blocks reach the comma-shaped singularity (Fig. 2). The advantage of this scenario compared to an embankment closed to the road is that the number of trajectories out of a plane normal to the embankment facing is limited. Indeed, it is believed that the risk of overtopping increases with the number of blocks having such a trajectory with respect to the embankment facing. For this reason it was decided to stop the blocks before being diverted by the singularity. The line drawn on Fig. 2 corresponds to the position of the crest of the projected embankment, on top of its mountain-side facing. It is referred to as the measuring line in the next sections. It can be noticed that a few trajectories bypass the north extremity of this line. Nevertheless, these were not considered for defining the embankment length as the resulting hazard on the road was less than the targeted hazard level.

2.4. Interception height

Fig. 4 gives the statistical distribution of the block passing height along the measuring line. The mean passing height is 1.07 m and the 99.9% cumulative passing height is 5 m. From this distribution it is possible to define the altitude of the crest of the embankment so that it stops a given percentage of the number of blocks passing through the measuring line. For this purpose the 99.9% value is considered in place of the maximum passing height

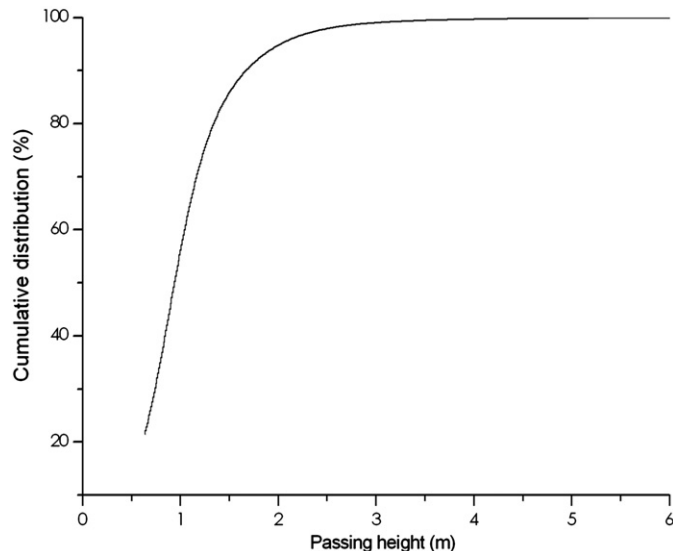


Fig. 4. Statistical distribution of the block passing height along the measuring line.

which by essence strongly depends on the number of simulations. As sometimes recommended [20] this height is increased considering a free board equaling the radius of the block. In this case a radius of 0.78 m is obtained considering a sphere of same volume as the cubic block. Finally, the interception height, i.e. the height of the projected embankment above the natural ground should be 5.78 m. It is worth highlighting that the passing height varies along the measuring line. The highest value is observed in the south part of the measuring line, closed to the topographical singularity between the two preferential paths. In an optimization process the interception height could be varied along the measuring line. For the sake of simplicity, a conservative approach is adopted here considering a unique value of interception height, based on the maximum value along the measuring line.

2.5. Assessment of the interception height

In a first step, a new set of simulations is conducted intercepting all the blocks passing below the determined interception height along the measuring line. The aim is to check that the interception height satisfactorily modifies the block run-out distances and hazard map. This preliminary assessment is performed before introducing the structure in the 3D digital terrain model, which is time consuming.

The assessment was performed rounding the interception height to 5.5 m. Results presented in Fig. 5 shows that the area exposed to rockfall is significantly reduced compared to the initial hazard (Fig. 2). Only 0.05% of the released blocks reach the road down the embankment, giving a maximum hazard of 0.002% per meter of road, far below the targeted value. Consistently with the location of the highest flying heights above the measuring line, this maximum is obtained downhill the south part of the measuring line. Of course, hazard resulting from trajectories not crossing the measuring line is not modified. In the case of blocks passing beyond the north extremity of the embankment the resulting hazard is below the targeted value.

2.6. Integration of the structure in the topography

Based on the validated interception height, the protection structure is integrated in the DTM which implies modifications of the slope profile and soil parameters. The slope profile changes

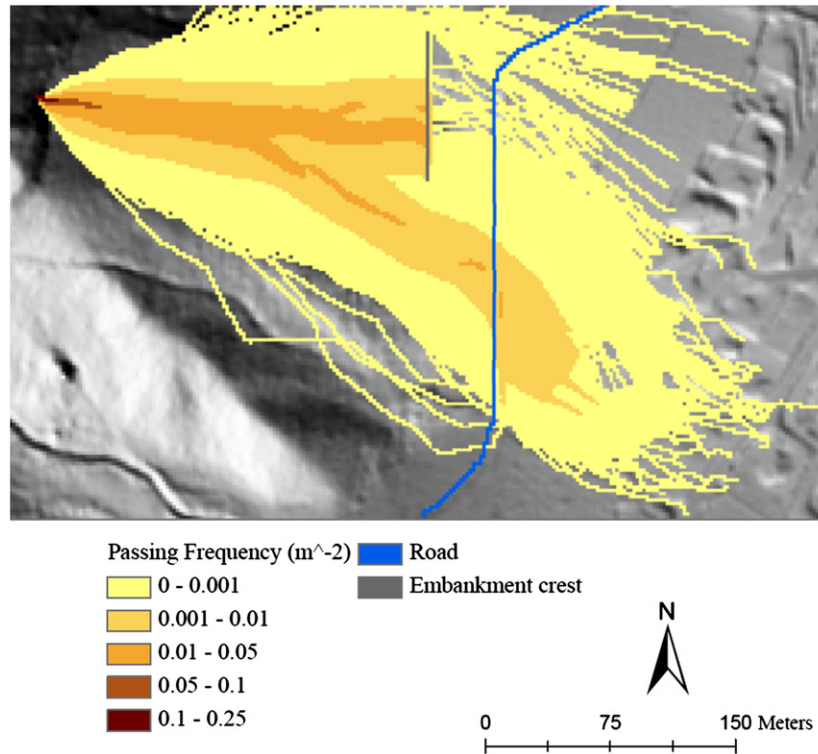


Fig. 5. Hazard map intercepting the blocks passing below a 5.5 m height along the measuring line.

Table 2
Characteristics of the surfaces.

	Slope uphill the ditch	Ditch	Embankment		
			Mountain-side facing	Crest	Valley-side facing
<i>Rn</i>	0.31	0.42	0.36	0.36	0.36
<i>Rg10</i>	0.05	0.05	0.05	0.05	0.05
<i>Rg20</i>	0.02	0.02	0.02	0.02	0.02
<i>Rg70</i>	0.01	0.01	0.01	0.01	0.01

result from the erection of the embankment, the digging of the ditch and the reshaping of the slope uphill the ditch. The embankment is positioned so that the toe of its mountain-side facing at the same altitude as the natural ground. Its height above the natural ground level is 5.5 m. The embankment crest width and its mountain-side facing inclination are 2 m and 70°, respectively. The ditch is 6 m in width and the slope uphill the ditch has an inclination of 45°. The crest width is consistent with engineering practices. The crest and ditch width have been determined as multiple of the spatial resolution of the model (2 m), for simplification purposes. The integration of the embankment in the DTM also results in changes in the surface characteristics, as presented in Table 2. The embankment was assumed to be composed of moderately compacted fine-grained soil material. Following Rock-*for3D* soil characterization and modeling methodology, such a material corresponds to a typical medium-ranged material. One can also note that *Rn* coefficient is slightly higher for the soil material of the ditch compared with the material of the embankment assuming that ditches can be assimilated to forest roads that are significantly more compacted.

Surprisingly, the simulation results presented in Fig. 6 show a small decrease in hazard compared to the initial hazard presented in Fig. 2 and an increase in hazard by comparison with Fig. 5. 46% of the released blocks reach the road down the embankment,

giving a maximum hazard of 0.9% per meter of road which is above the targeted value.

A detailed analysis of the block trajectories revealed some abnormal block flying heights after impact on the embankment. Fig. 7 gives the value of the extreme flying heights on each raster cell, based on the 95% estimator (mean value plus twice the standard deviation). This estimator reached values higher than 30 m above the natural ground are observed downhill the embankment. In a practical context, a design engineer would exclude the corresponding data based on its experience and without any objective criteria.

Basically, these results suggest that the simulation tool can not reproduce the ability of the embankment in intercepting the blocks and, on the contrary, acts as a springboard.

2.7. Limitations

The results presented in the previous section are counter intuitive and question the validity of the tool in modeling the block trajectory in the vicinity of the embankment. Two limitations concerning the spatial resolution and rebound model explain these results.

2.7.1. Spatial resolution

The spatial resolution of the DTM is 2 m. This resolution affects the slope profile description (Fig. 8). The real topography in the vicinity of the embankment is not satisfactorily modeled in terms of slope angles. The horizontal surface associated to the ditch is reduced to a 2 m in width surface instead of 6 m and the horizontal surface associated to the embankment crest does not appear. The embankment facing has a calculated inclination of 52° instead of 70°, and this value is associated to a cell located in the ditch. As a matter of fact, there is no cell associated to the facing. Globally, the slope changes in the vicinity of the embankment are smoothed in the DTM. Basically, the aspect and the slope

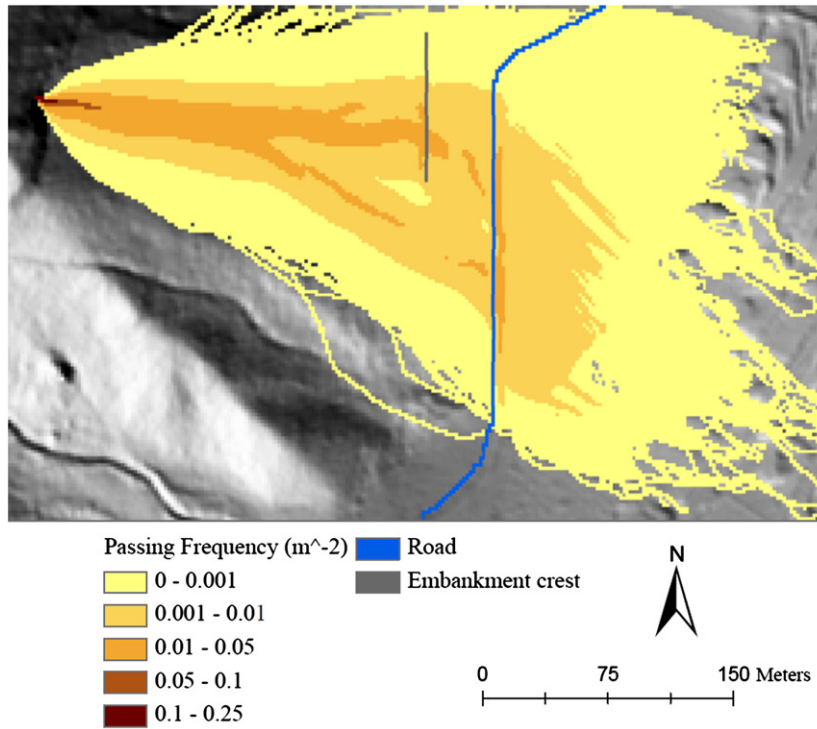


Fig. 6. Hazard map integrating the protective structure.

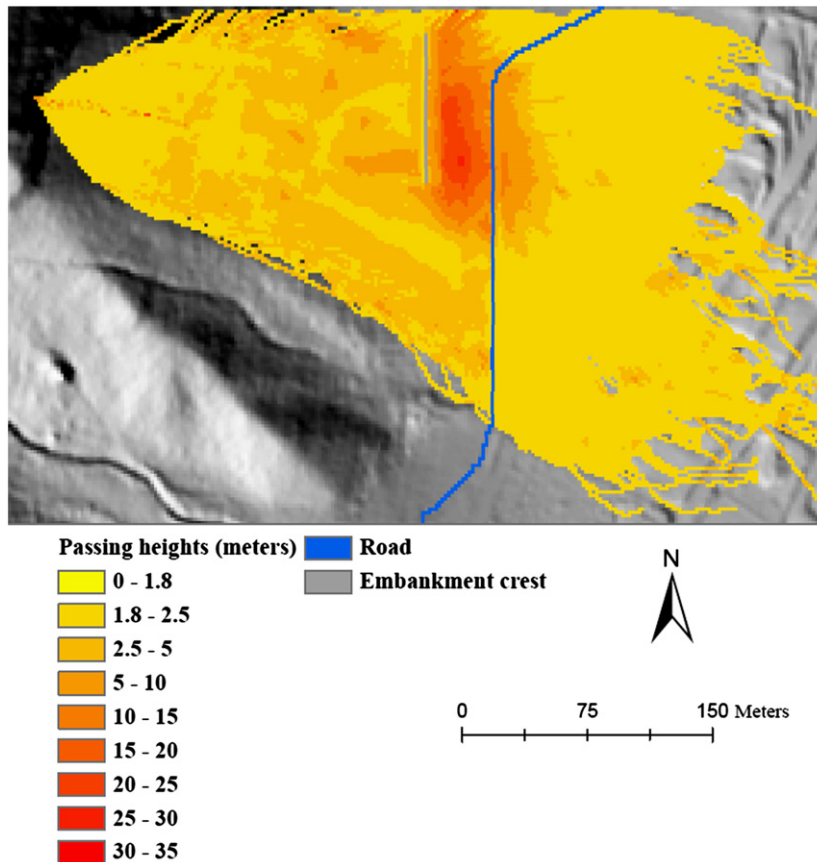


Fig. 7. Passing heights map revealing abnormal trajectories.

associated with each cell are calculated from the values of the elevation of the neighboring cells. Depending on the resolution of the rasterized DTM method may result in a significant profile

smoothing and in incorrect slope angles. This has consequences on the location of the impact point and on the tangential and normal impact velocities. Obtaining relevant slope values for the

cells associated with the embankment would require describing each surface of the embankment using a large amount of cells, implying an increase of the DTM resolution.

Such a solution is in contradiction with the DTM resolution range for an efficient use of trajectory simulation codes, at the site scale. First, the computation time would increase dramatically with an increase in DTM resolution. Second, 3D rebound models are not valid when the DTM resolution is too small compared to the block size. This difference between the relevant resolution range for a precise description of the embankment geometry and for the use of the rebound models induces inconsistent results. In particular, this undoubtedly contributes to the large passing height observed. The important smoothing of the embankment geometry induces the embankment to be modeled as a spring-board that can be easily overtopped by the rocks, increasing both the passing heights and hazard in the downhill raster cells.

2.7.2. Rebound model calibration

High passing heights also result from limitations in the rebound model and its calibration. As illustrated in Fig. 9, the rebound is really different in case of an impact on the embankment mountain-side facing as compared to an impact on the slope. The differences concern both the trajectory before and after the impact. The range of the angle between the block trajectory and the normal to the impacted surface differs between the two cases. In the embankment rebound case, both impact and rebound angle ranges are much larger. Moreover, in the slope

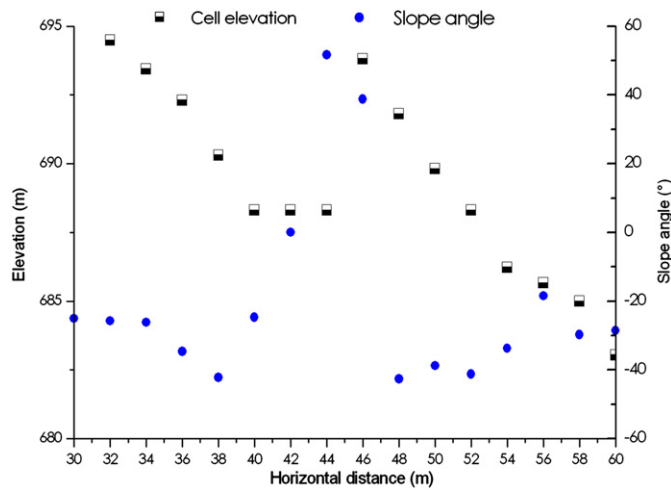


Fig. 8. Site topography descriptors as deduced from the DTM with a 2 m-resolution.

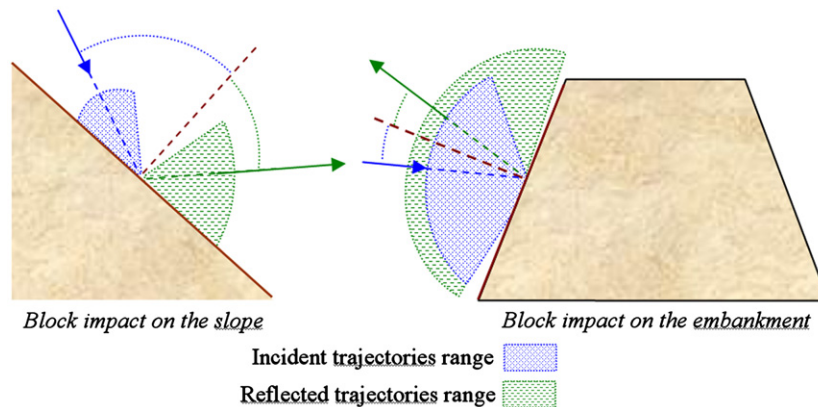


Fig. 9. Typical ranges of incident and reflected block trajectories in case of a rebound on the slope and on the embankment mountain-side facing.

rebound case, this angle is strictly negative for the impact direction and positive for the rebound direction while in the case of the embankment both angles can either be negative or positive. Trajectories that are normal to the surface are impossible in the first case while frequent in the second. Coupling between translational and rotational velocities are thus expected to be different in the two cases. Classical restitution coefficients have mainly been calibrated based on observations after real events or on tests in the lab both on rather steady slopes, where impact angles are shallow with typical average inclinations ranging from 0° to 45° . For these reasons, usual restitution coefficients may not be appropriate for modeling the rebound on the embankment facing and, to a lesser extent, in the ditch. In particular, impacts normal to the embankment may result in very high tangential rebound block velocities, leading to unrealistic flying heights and thus to an excessive embankment over topping occurrence.

In addition, the couplings between the translational and the rotational velocities are expressed in a very simple manner in rockfall simulation codes. This is not limiting at the slope scale but it could be at the structure scale where overtopping may result from a high rotational velocity [21]. For example, in the current version of Rockyfor3D, the coupling between the translational and the rotational velocities is modeled considering that the rock does not slip during impact on the soil surface [15] which is sufficient to model the evolution of the velocities of the rock at the slope scale [10] but may result in abnormal results at the structure scale.

In order to solve these problems, and in the absence of experimental data concerning the rebound in such configurations, a new rebound model is proposed in the following section.

3. Alternative modeling approach coupling local trajectory modeling with rockfall simulation codes

3.1. Description of the model

The approach developed to cope with the limitations of classical 3D rockfall simulation codes in terms of spatial resolution and rebound modeling consists in simulating the propagation of the rock through the DTM, using RockyFor3D, except in the neighborhood of the structure where a special model is used. This local model provides an exact profile description and uses a specific rebound modeling in the vicinity of the embankment.

The two models are spatially coupled thanks to two linear interfaces, corresponding to two groups of raster cells of the DTM. The first one is the frontier between the natural slope and the re-profiled slope uphill the ditch and the second one is the limit of the downhill limit of the embankment valley-side facing.

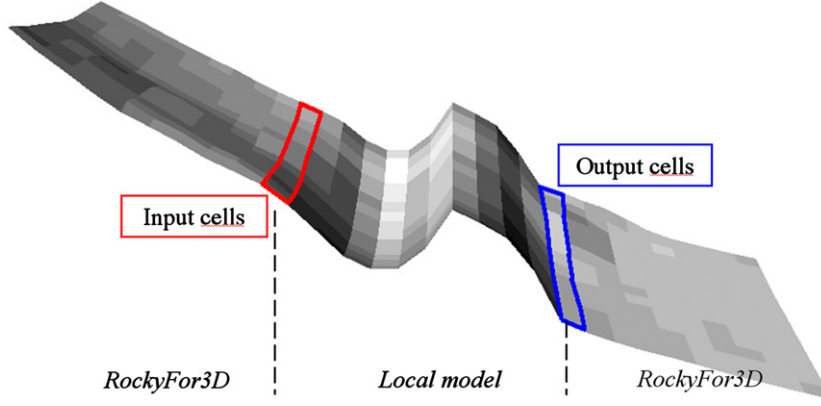


Fig. 10. Definition of the input and output cells in the Digital Terrain Model defining the limits of the model at the slope scale and at the local model.

Data from Rockyfor3D are collected in the first interface cell group (Fig. 10), called input cells group, to be used as input data for the local model. Similarly, after propagation in the model at the structure scale, the data collected in the second group of cells, called output cells group, are used as initial conditions for the propagation of the rock on the natural slope downhill the embankment simulated by Rockyfor3D.

For each rock propagating through a cell of each group, a set of exchange parameters is stored. Considering the block propagation along the slope, and consequently from one spatial model to the other, the exchange parameters are first transferred from the model at the slope scale to the model at the structure scale and, second, from the model at the structure scale to the model at the slope scale. There are two exchange files that, respectively, allow exchanging the parameters from Rockyfor3D to the local model (input exchange file) and from the local model to Rockyfor3D (output exchange file). The exchange files are classical ASCII files. Each line of these files corresponds to a set of parameter associated with a propagating block.

As both models are dedicated to the propagation of the rock blocks, the relevant exchange parameters for each block are the location and the velocities of the blocks at the spatial interfaces between the two models. More precisely, the stored parameters were the magnitude of the translational and rotational energies, the direction of the initial velocity of the rock—characterized by two angles (towards a horizontal and a vertical plane) and the flying height of the rock.

At the local scale, the embankment topography is modeled as an exact profile defined in the rock propagation direction. It is defined for each free flight phase between two rebounds. This profile corresponds to the intersection between the plane associated with the trajectory of the rock and the surface characterizing the topography of the embankment (Fig. 11). Similarly as in Rockyfor3D, the plane associated with the trajectory of the rock changes after each rebound depending on the rock lateral deviation. For each free-flight phase, the calculation of the intersection between the above mentioned profile and the parabola describing the trajectory of the rock gives the consecutive impact point. This calculation is exact as an analytical solution exists for the intersection between a parabola and a multi-linear profile. The use of this analytical solution allows coping with the resolution issue while keeping the 3D character of the simulation.

The limitation of current rebound models for normal impacts is due to nonrelevant calibration of the parameters and to simplified modeling of couplings between the different components of the translational and rotational velocities. Consequently, the choice was made to use a stochastic rebound model calibrated for any incidence angle from shallow to normal impacts [16]. This stochastic rebound

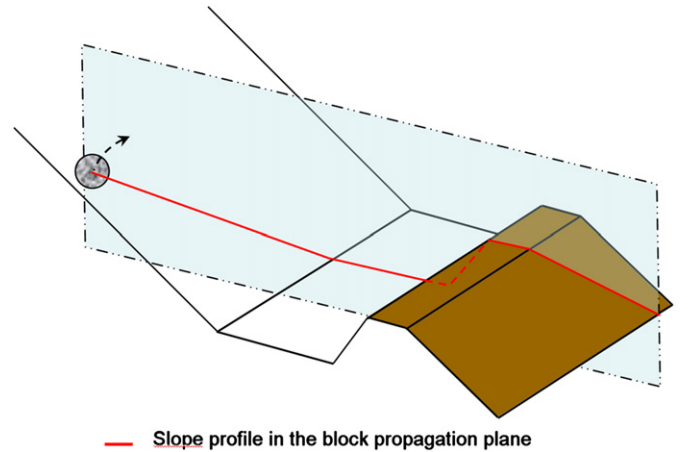


Fig. 11. At the structure scale, the slope profile in the block propagation direction is recalculated after each impact.

model is built from the statistical analysis of numerical results obtained from impact simulations. The approach consists in using impact simulations at a local scale to capture the main processes governing the rebound and the variability of this phenomenon. Such simulations make it possible to obtain large sets of results under the same conditions by comparison to rockfall events or field experiments. Contrary to classical approaches, the model proposed is directly developed in a global stochastic framework whereas classical approaches are based on deterministic models combined with variable parameters.

The different components of the rebound velocity of the boulder are calculated using this stochastic rebound model from the components of the impact velocity. In a 2D context, the kinematical parameters of the boulder are properly described by a generalized velocity vector V that is composed of a velocity component along the direction normal to the soil surface V_n , of a velocity component along the tangential direction to the soil surface V_t and of a rotational velocity ω such as: $V=[V_t V_n \omega]$. The impact V^{in} and rebound V^{re} velocity vectors are related by a stochastic operator. The first order Taylor series expansion of this operator leads to the definition of the operator A composed of nine coefficients a_i [16]:

$$vV^{re} = AV^{in} \quad (1)$$

The high variability of the local configurations of the soil and of the impact kinematical conditions induces that the operator A cannot be considered as a deterministic variable. A stochastic approach is therefore adopted to capture the variability associated with the operator A .

For gravel-like materials, a numerical approach based on the Discrete Element Method [23] was used to model impacts and to perform an intensive simulation campaign. The statistical analysis of the numerical results was carried out leading to the definition of the stochastic rebound model. A detailed description of the numerical model of the impact can be found in Bourrier et al. [13]. It is also important to note that the relevance of the impact model has been proved by comparison with results from the literature [13] and from half-scale experiments of impacts on a coarse soil [24]. A result database was built from all simulation results performed for varying impact points and impact kinematical conditions and for fixed soil macroscopic and boulder properties. The numerical results were treated using a statistical analysis to build the stochastic rebound model relating impact and rebound kinematical parameters. The variability of the values of the coefficients of the operator A are captured by the statistical analysis using a normal probability distribution function characterized by a mean vector M_A and a covariance matrix Σ_A . For the integration of the stochastic rebound model in the coupled trajectory simulation model, values of the parameters M_A and Σ_A corresponding to impact of a rock at least 10 times larger than the mean size of the soil particles on a 2 m deep moderately dense soil were taken. This set of parameters has already been used to model impact on gravel-like materials [11]. The stochastic rebound model was then used at the local scale for impacts on the horizontal ditch and on the mountain-side facing of the embankment.

3.2. Results based on the coupled models approach

The results obtained were analyzed both at the local and slope scales with the aim of evaluating the relevance of the coupled approach.

At the slope scale, Fig. 12 shows that the abnormal results previously obtained are coped with by the coupled approach. In this figure, the area covered by the local model appears in white,

without any data concerning passing frequencies. The passing frequencies resulting from blocks going out of the local model appear in a different color scale than the other ones. The blocks propagation is well controlled by the embankment: only 0.07% of the rocks passing through the input cells of the local model over passed the embankment and only one block reached the road. The maximum hazard along the road down the embankment vanishes to 2.10–4% per meter of road.

The comparison of this map with the map obtained intercepting the blocks passing below a 5.5 m height along the measuring line (Fig. 5) shows a significantly higher hazard reduction than expected. The number of blocks overtopping the embankment is much less with the structure. This suggests that the change in profile along the slope as well as the modification of the normal restitution coefficient, with a reduction on the average, significantly improves the efficiency of the protective structure, decreasing the hazard.

The qualitative analysis of the rocks trajectory in the vicinity of the embankment revealed various trajectory scenarios. A vast majority of the blocks entering the local model impacted the ditch, with variable energy loss, before bouncing. By contrast, only 12% of the blocks directly hit the embankment mountain-side facing without any rebound in the ditch. A very limited number of blocks lobbed both the ditch and embankment. This trend results from the broadness of the ditch: the wider the ditch the higher the number of blocks falling in the ditch. Direct impacts on the embankment are characterized by a high block impact kinetic energy. Nevertheless, a quasi-total block kinetic energy loss was observed for two of these blocks out of three.

4. Discussion

Trajectory analyses are either conducted using 2D or 3D representations of sites. The choice is not neutral in terms of hazard evaluation as these approaches rely on different methodologies. In 2D, the residual hazard is calculated along one or

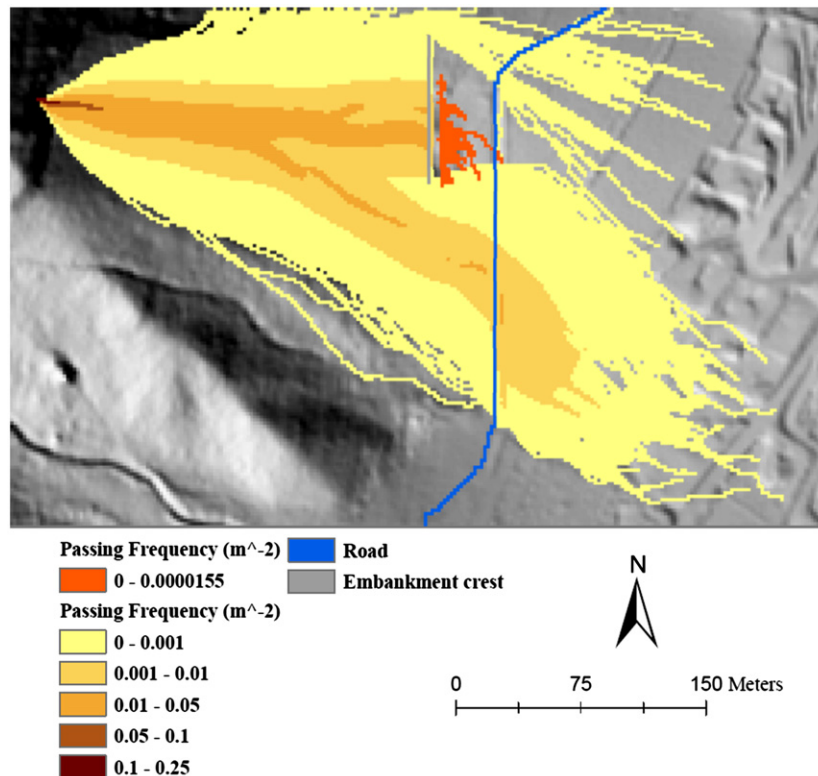


Fig. 12. Hazard map integrating the protective structure using the coupled approach.

a limited number of profiles crossing the embankment. In 3D, the detailed topography can be modeled. If a linear stake is considered, the hazard can be assessed for each point on the stake in 3D whereas it is a unique value in 2D. Moreover, the value provided by the 2D analysis is a mean value, possibly hiding high level hazard areas along the road. 3D approaches reveal these areas and allow for an optimized design of the embankment along linear stakes.

Nevertheless, 3D approaches require defining the hazard depending on the nature of the stake and the aim of the trajectory analysis. The hazard may be expressed per unit surface when dealing with a hazard map (i.e. % of occurrences/m²) or per unit length in case of a linear stake (i.e. % of occurrences/m of stake). This is not an issue with 2D approaches. As a consequence, limit values for the evaluation of hazard, as given by local regulations for instance, should be adapted depending on the type of approach considered (2D/3D) and also on the use of the trajectory analysis results.

This study has highlighted that 3D rockfall simulation codes should be used with caution when designing an embankment. In the vicinity of the protective structure, the DTM resolution, generally ranging from 1 m to 10 m, does not result in a correct representation of the geometry of the embankment. These resolutions are required for an efficient use of 3D rockfall simulation codes at the slope scale but are not precise enough for accounting rapid slope inclination variations as observed in the vicinity of the embankment. While the raster resolution has been shown to have a strong influence on the lateral dispersion of trajectories at the site scale [18], its influence on the block kinematics has never been discussed while it may result in abnormal trajectories. Consequently, specific methodologies providing a more precise slope description should be developed, for example by coupling models with different resolutions, as proposed in this paper.

It appeared that rockfall modeling in the presence of an embankment was also confronted to a limitation concerning knowledge on restitution coefficients. Both 2D and 3D currently used trajectory analysis tools make use of coefficients calibrated based on inclined impacts. This significantly differs from the case of an impact of a block on the steep mountain-side facing of an embankment in particular. Improving the efficiency of trajectory analysis tools in modeling the trajectory in such a context requires developing and implementing specific rebound algorithms calibrated for these particular impact conditions. Reaching this aim requires conducting laboratory or field experiments varying the impact angle, as recently conducted by Asteriou et al. [25].

In addition, regarding the relevancy of local models although very complex, it is important to note that the interaction between the block and the embankment depends not only on the pre-impact block velocity amplitude and orientation but also on the global embankment response, which in particular depends on the location of the impact point on the embankment mountain-side facing. An impact close to the embankment crest will lead to a higher embankment deformation than at its mid-height, modifying the block rebound [21]. The restitution coefficients are thus not intrinsic to the embankment facing materials. And, the resulting embankment deformation may result in an increase in the probability of over-topping. This issue is all the more critical since it may affect dramatically the residual hazard: neglecting this effect means underestimating the residual hazard.

One can note that, beside the specificities of the code used for this study, it can be considered representative of currently used tools: 3D rockfall simulation codes have to face with spatial resolution problems as well as rebound models formulation and calibration problems [18]. Nevertheless, in the case of codes using triangulated irregular network (TIN) for the DTM, the resolution

problem can be solved by increasing the resolution in the embankment vicinity.

As an alternative to the rather simple but satisfactory rebound model proposed in this paper, any model at the structure scale may be used with the aim of computing the trajectory of the block in the vicinity of the embankment, taking into account their effective interaction. For instance, computations based on finite element models [5] or on discrete element models [21] of the structure could be used. This would certainly help compensating the lack of knowledge concerning the mechanical interaction between block and embankment, in particular given the variety of possible facing materials.

However, in this study, the aim was to solve the resolution and rebound model problems associated with simulations at the slope scale with a limited increase in complexity. The model developed at the structure scale is therefore a simple approach able to solve both problems. The number of required parameters is limited and the computational duration remains small, by comparison with FEM and FEM based methods. This local model thus allows for large number of simulations as well as parametric studies.

The comparison of the results from the validation of the embankment interception height and those from the integration of the embankment in the DTM showed that the changes uphill the embankment strongly affects the propagation of the blocks. In this case, a significant hazard reduction is observed, in particular due to the ditch width. Depending on the site topography, ditch width and reprofiled slope inclination other influences may be observed. The design of embankments with respect to their ability in controlling the block trajectories may be improved considering the influence of the ditch width and the embankment vertical batter. For the latter parameter, minimum values have been proposed without any objective base, while considering some technical limits regarding the constructability.

5. Conclusion

Up to now, the relevance in using trajectory analysis tools for the design of embankments as well as for assessing the hazard downhill such protective structures has not been investigated in detail. This study has shown that currently used codes may fail in accurately modeling the site topography, due to the limited resolution by comparison with the rapid profile changes in the embankment vicinity. In addition, the current restitution coefficients are not appropriate for modeling the block-soil interaction as these have mainly been calibrated for shallow impacts which are not relevant for impacts on embankment mountain-side facings.

A model has been proposed coupling a classical trajectory tool at the slope scale to a local trajectory model in the embankment neighborhood. This model accounts for the real site topography and considers a stochastic block-soil interaction model with a broad inclination angle validity range. In the future, it will be possible to use this method to satisfactorily account for the influence of the inclination of the mountain-side embankment facing as well as the ditch width and fill material, in particular. In parallel, research concerning the interaction between the embankment and the block are necessary in order to improve the rebound modeling, through specific restitution coefficients for integration in currently used trajectory analysis tools.

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