GIS-Based Rockfall Hazard Assessment in Support of Decision Making

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ABSTRACT: When designing infrastructure, settlements or facilities in mountainous areas, rockfall hazard assessment is considered essential, as it is a major hazard worldwide. Rockfall hazard estimation can help greatly in the design of countermeasures, such as barriers and net fences, in order to protect the built environment, as well as for landuse planning. Rockfall modelling is considered an effective way of estimating rockfall hazard despite the complicated processes involved. In this paper, a new three-dimensional rockfall simulation model, developed in the GIS environment, is proposed as a tool for assessing rockfall hazard for a local- or regional-scale area. The model, adopting a kinematic approach, can simulate rockfall trajectories based on the topography, the frictional characteristics of the ground, the magnitude and direction of the initial velocity and the restitution coefficients on the block velocity. The model is implemented in an application, called ROCKFALL ANALYSIS, running in the ArcGIS environment allowing stochastic analysis and, even more, three-dimensional visualization and animation of rockfalls. By means of case studies we evaluate both the simulation model and the application as a tool assisting spatial analysis and planning, which can be used in decision-making and design concerning transportation infrastructure or large technical works, such as dams.

1 INTRODUCTION

1.1 Rockfalls

The phenomenon of rockfalls is quite common especially in mountainous areas and man-made slopes. The high energy, mobility, spatial and temporal recurrence are the characteristics that make rockfalls one of the most important natural hazards worldwide. They can threaten lives, roadways, settlements and facilities having tremendous consequences.

After a rockfall is triggered, the rockfall trajectory is a combination of four main processes, namely: sliding and/or toppling, free falling, bouncing (impact) and rolling, where impact is considered the most complex, uncertain and poorly understood stage (Broili, 1973). All these processes depend on laws of mechanics and a model used to describe rockfall trajectory can have various levels of complexity.

The main factors controlling rockfalls is the geometry and the material properties of the slopes. Other factors, such as the size and shape of the rock boulders, the coefficients of friction of the rock surfaces and whether or not the rock breaks into smaller pieces on impact are all of lesser significance (Hoek, 1998).

1.2 Rockfall modeling

When dealing with landuse planning and the design of countermeasures against rockfalls (e.g. design of slope benching, retaining fences, fills, ditches) in mountainous areas, rockfall hazard assessment is considered requisite. A reliable way of assessing rockfall hazard is rockfall modeling, which can assess “the envelope of trajectories, the maximum run out distance, the distribution of kinematic parameters along a path, the probability for a specified “design block” to stop at specific distances from the starting point (Agliardi and Crosta, 2003), etc.

As strange as it may seem rockfall is not a simple process to model. The parameters controlling a rockfall, such as the location of the source area, the boulder’s shape and geometry, the mechanical properties of the rock and the slope, and the topography (Ritchie, 1963) are difficult to be precisely determined due to their wide variation.

Therefore, rockfall behaviour can be variable and complex and estimating rockfall trajectory is a complicated operation incorporating a wide margin due to uncertainty. Stochastic analysis is an effective way to deal with this uncertainty, by varying the parameters incorporated into the model (e.g. mass, shape, size, restitution and friction coefficients) according to probability density distributions, as well as considering a number of blocks rather than a single one. Many rockfall models include a Monte Carlo simulation technique to vary the incorporated parameters.

The most crucial part in simulating rockfalls using a mathematical model, which define its reliability to a large extent, is the definition of the right amount of energy lost by rock blocks during the impact with the ground as well as the direction they will follow afterwards. Finding the right amount of energy lost is a difficult task as the relationships linking the energy loss to different variables, such as the slope roughness, the geotechnical properties of the slope and the block shape and dynamics, are not clearly defined.

A two-dimensional (2D) approach is favored from an operational and computational point of view, yet the interpretation of the results and their extension to neighbouring areas is subjective (Crosta and Locatelli, 1999). When using a 2D model, the simulation is performed along user-specified pre-defined slope profiles neglecting the three-dimensional (3D) effect of the topography, an effect playing a major role in controlling the dynamics of falling blocks. This is a severe limitation especially in areas where minor changes in topography influence a rockfall, e.g. along steep channels, where the topography is concave or convex or at the apex of a fan (Crosta and Locatelli, 1999).

3D rockfall simulation models are better than 2D models as they take into account the 3D effect of topography on rockfalls. The most important effect is the "lateral dispersion" of rockfall trajectories (Crosta and Agliardi, 2004), i.e. the ratio of the lateral distance separating the extreme fall paths to the slope length (Azzoni et al. 1995). The occurrence of lateral dispersion makes it difficult to choose a priori the right rockfall path when a 2D approach is adopted (Agliardi and Crosta, 2003).

2 GIS-BASED ROCKFALL HAZARD ASSESSMENT

Over the last decade, the widespread availability of Geographical Information Systems (GIS) and the improvement of GIS technology have given engineers the possibility to conduct different kinds of landslide hazard assessments for a local- or even a regional-scale area by the use of simplified geotechnical models. GIS can now be the platform where hazard occurrence models can be developed, permitting evaluation of results and adjustment of the input variables (Sakellariou & Ferentinou 2001, Ferentinou 2004, Sakellariou et al. 2006). In addition, GIS allow management and analysis of large amounts of spatial data and support the zonation of large areas.

In this paper an application called ROCKFALL ANALYSIS is presented. ROCKFALL ANALYSIS is developed in a GIS environment and is capable of performing rockfall hazard assessment for an area, local- or regional-scale, in a 3D space. This assessment is based on a new 3D rockfall simulation model, first created in 2006 (Charalambous), which, adopting a kinematic approach, simulates 3D rockfall trajectories based on a number of spatial or non-spatial input data

2.1 *The Application ROCKFALL ANALYSIS*

The application is developed within the software ArcGIS. Is written in VBA and is comprised by two basic sections. The first section, "ROCKFALL_ANALYSIS.mxd," runs within the program ArcMap (Fig. 1a). The calculation of the 3D rockfall trajectories is performed in this section and simulated rockfalls are represented in 2D (plan view). Furthermore, extra output data, spatial or not, can be produced within this section.

"ROCKFALL_ANALYSIS_3D.sxd" is the second section. It runs within the program ArcScene (Fig. 1b) and is responsible for the 3D visualization and animation of the simulated rockfalls and the 3D representation of any other spatial data. Non-spatial data can also be presented here.

ROCKFALL ANALYSIS runs in each section using the toolbars (Fig. 1). Apart from the functions the application offers, ArcMap and ArcScene offer a vast range of other useful functions to the users (e.g. mapping, analysis, exporting, printing, etc.), helping them in achieving a more integrated and credible rockfall hazard assessment.

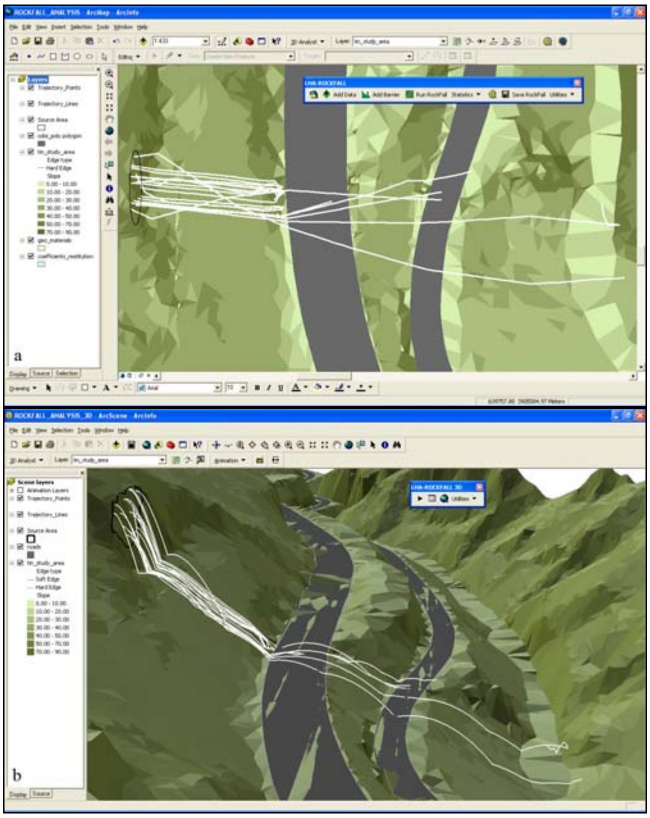

Figure 1. a. The first section of ROCKFALL ANALYSIS running in ArcMap b. The second section of ROCKFALL ANALYSIS running in ArcScene.

2.2 *The Rockfall Simulation Model*

2.2.1 *Assumptions, Input and Output Data*

Rockfall modeling is accomplished by the use of the proposed 3D rockfall simulation model. As it is impossible to model accurately any physical phenomenon a number of assumptions have been made regarding the model:

- The model deals only with single block falls and mass falls, also called "fragmental rock falls" (Evans and Hungr, 1993), where the interaction among the falling blocks is considered null or negligible.
- A kinematic approach, treating the falling block as a lumped mass, allows free fall, bouncing/impact, rolling and sliding motions modeling in a 3D framework.
- The influence of the shape, the size and the angular momentum of the rock boulders on rockfall trajectories is only taken into consideration when rolling occurs. While in air, a boulder's velocity is considered only translational, i.e. rotational velocity is ignored.
- Topography is represented by a Digital Terrain Model (DTM) in a Triangulated Irregular Network (TIN) format, without resolution restrictions. In this way, the 3D effect of the topography is taken into account.
- A number of input data (e.g. geology, restitution coefficients) are spatially distributed within the study area, using the ESRI shapefile format.
- The rockfall source can be defined by a point, polyline, polygon, rectangle, circle or an ellipse. When the source area is described by a polyline or a surface a set of rock boulders (the number is specified by the user) can be thrown from points along the polyline or within the

surface. In that way, a form of stochastic modeling can be performed. For the moment, the source area (initial position of rocks) is the only parameter of the model defined as a random variable.
- Air drag and block fracturing are not taken into account.

The input data required by the model are divided into spatial and non-spatial data. The spatial data are:

- The TIN representing the 3D topography of the area;
- A polygon shapefile containing the friction characteristics of the ground (friction angle of the geological formations);
- A polygon shapefile containing the normal and tangential restitution coefficients of the ground (in terms of velocity) on the block velocity;
- The rockfalls' source area.
- The model allows additionally the design and the implementation of barriers (3D polygon shapefile), vertical or non-vertical, as a countermeasure. The model takes into account the characteristics of the barrier (location, geometry, frictional characteristics and restitution coefficients) when calculating the rockfalls.

The necessary non-spatial input data are the magnitude and the direction of the initial velocity and the magnitude of the velocity which defines the transition point between the projectile state and the state where the rock is moving too slowly and, thus, should be considered rolling, sliding or stopped; This limit velocity is called minimum velocity.

While the application produces 3D output data as results, in order to enhance the information generated, qualitative data are also generated referenced to the output spatial data. Specifically, the output data are:

- A 3D point shapefile containing all the points created along the rockfall trajectory. For each point non-spatial data are provided into the shapefile's Attribute Table, e.g. the Id of the rockfall, the location (X,Y,Z) of the rock boulder, the height above the ground surface and the velocity (V_x,V_y,V_z) at that location, the time passed since the initiation of the rockfall, the aspect (aspect is the dip direction of the Tin triangle), the slope, the friction angle and the restitution coefficients of the underlying slope and comments for the present state of the boulder.
- A 3D polyline shapefile containing all the rockfalls simulated. The length and the duration of each rockfall are given in the attribute table.
- A table with statistics for each rockfall (e.g. total horizontal and vertical movement, total duration and length, maximum velocity and height DZ above ground) as well as for the whole set of the rockfalls (e.g. minimum and maximum length, duration and DZ).
- A 3D real time animation of the simulated rockfalls.

2.2.2 Initial Conditions

Each rock boulder starts its rockfall from a point (X_0, Y_0, Z_0) within the source area and upon or above the ground surface, having a translational initial velocity $V_0(V_{0X}, V_{0Y}, V_{0Z})$. Setting an initial velocity greater than zero also assists in the execution of a seismic hazard assessment.

2.2.3 Bouncing/Impact

When the velocity V_0 is greater than $V_{\min}$, then the rock boulder follows a parabolic path through air, described by simple kinematic laws (Charalambous, 2006), until it hits the ground surface. Impact with the ground is the most complex, uncertain and poorly understood process of a rockfall because the relationships linking the energy loss to a number of variables (the slope roughness, the geotechnical properties of the slope and the block's shape and dynamics) are not clearly defined (Agliardi and Crosta, 2003). In the proposed simulation model, the impact is considered partially elastic, to a grade depending on the restitution coefficients. Though in 3D space, tangential (R_t) and normal (R_n) restitution coefficients are used.

When impact occurs, energy is lost and the direction of motion of the rockfall changes depending on the slope's 3D geometrical (slope, aspect) and mechanical properties (R_t, R_t). When the point of impact (X_{imp}, Y_{imp}, Z_{imp}) and the impact velocity (V_{Ximp}, V_{Yimp}, V_{Zimp}) are calculated, then the impact velocity is transformed from the Global Coordinate Cartesian System XYZ to a Local Coordinate Cartesian System. A Cartesian System UVW (Fig. 2), local to the TIN triangle (each triangle represents a slope) is used. The System UVW is defined by the impact point as the point of origin, the axis U tangential to the slope and towards the steepest downslope direction, axis W perpendicular to the slope and axis V tangential to the slope. The vector of the impact velocity in the UVW Cartesian system will be:

$$\begin{pmatrix} V_U \\ V_V \\ V_W \end{pmatrix} = [R] \cdot \begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix} \tag{1}$$

where [R] is the transformation matrix of the Equation 2.

$$[R] = \begin{pmatrix} \cos(\theta)\cdot\cos(\omega) & \cos(\theta)\cdot\sin(\omega) & -\sin(\theta) \\ -\sin(\omega) & \cos(\omega) & 0 \\ \sin(\theta)\cdot\cos(\omega) & \sin(\theta)\cdot\sin(\omega) & \cos(\theta) \end{pmatrix} \tag{2}$$

The transformation involves two rotations (Fig. 2): a rotation of the Cartesian System XYZ about Z axis for an angle ω = Aspect – 90 and a rotation of the previously transformed system about V axis for an angle θ = Slope Angle.

The next step is to reduce the impact velocity, referenced to UVW Cartesian System, according to the restitution coefficients. This is accomplished by the use of Equation 3.

$$\begin{pmatrix} V_{U\_after} \\ V_{V\_after} \\ V_{W\_after} \end{pmatrix} = \begin{pmatrix} R_t \\ R_t \\ R_n \end{pmatrix} \cdot \begin{pmatrix} V_{U\_before} \\ V_{V\_before} \\ V_{W\_before} \end{pmatrix} \tag{3}$$

Finally, the new, post-impact velocity is calculated by transforming the velocity back to the Global Coordinate Cartesian system XYZ using Equation 4:

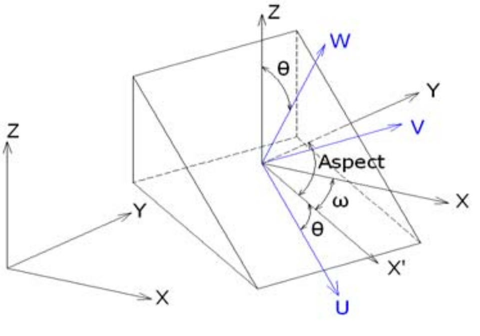

Figure 2 – The relationship between the two reference coordinate Cartesian systems of the rockfall simulation model: the "Global" coordinate system (XYZ) and the "Local" coordinate system (UVW) (Charalambous, 2006).

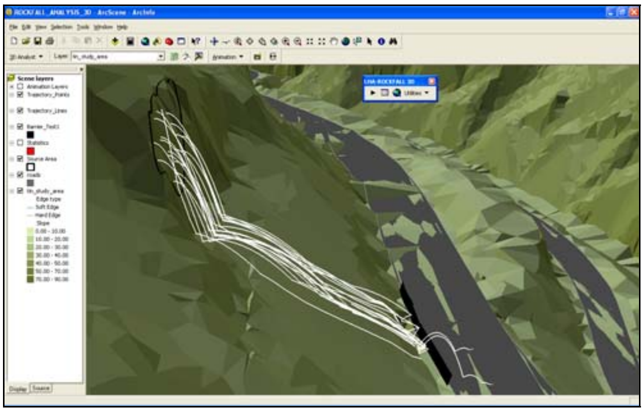

Figure 3: Rock fall simulation in the case where a barrier is used as a countermeasure.

Figure 4: The 3-D animation of rock falls in “Rockfall Analysis” application.

$$\begin{pmatrix} V_{X\_new} \\ V_{Y\_new} \\ V_{Z\_new} \end{pmatrix} = [R]^{-1} \cdot \begin{pmatrix} V_{U\_after} \\ V_{V\_after} \\ V_{W\_after} \end{pmatrix} \qquad (4)$$

The normal to the slope component of the post-impact velocity, $V_{\mathrm{W\_after}}$, is then compared to $V_{\min}$. If $V_{\mathrm{W\_after}} > V_{\min}$ then the bouncing continues but if $V_{\mathrm{W\_after}} < V_{\min}$ then the rock boulder stops bouncing and starts sliding or rolling along the slope’s steepest path.

2.2.4 Sliding and Rolling

Whether the movement is sliding or rolling is determined by the ground’s friction coefficient and the slope angle. Taken that rock boulders have circular shape (radius R and mass m) then rolling occurs when slope angle θ is smaller than

$$\theta_{\max} = Arc\tan\left(\tfrac{7}{2} \cdot \mu_s\right) \qquad (5)$$

where μ_s = friction coefficient. When the slope angle θ is greater than $\theta_{\max}$ then the movement taken place is sliding.

The influence of rolling or sliding on the simulation model is expressed by the constant K (Hoek, 1987) used in Equation 6 for the calculation of the exit velocity

$$V_{EXIT} = \sqrt{V_{0UV} - 2 \cdot s \cdot g \cdot K} \qquad (6)$$

where $V_{0\mathrm{UV}}$ = the initial velocity of the rock tangential to the segment, s = is the distance from the initial location to the endpoint of the segment towards the slope’s steepest direction and g = is the acceleration due to gravity. When the assumed condition is pure sliding then $K = \pm\sin\theta - \cos\theta \cdot \tan\phi$, where φ = the friction angle, and when the assumed condition is a rolling sphere then $K = \pm(5/7) \cdot \sin\theta$. The symbol ± is + if the initial velocity is downslope or zero and - if the initial velocity is upslope.

The simulation model has the great advantage of including the case where a rock boulder rolls/slides along a V shaped concave surface. While in other simulation models this would cause them to enter an endless calculation loop, and “crash” (to deal with such a problem**,** the models would take countermeasures (e.g. give each rock a certain amount of real time to finish all of its calculations had to be taken)), this does not occur in the proposed model, in which a rockfall simulation stops only due to reasons regarding the phenomenon of rockfalls.

2.3 Barriers

Implementing barriers as a remedial measure in the simulations is undoubtedly a very useful tool for engineers as it expands their design capabilities, especially when dealing with road construction or when protection of settlements, monuments, or technical works against rockfall is required (Fig. 3).

Barriers in ROCKFALL ANALYSIS have the same influence on rockfalls as any other slope in the DTM. They are created within the application and they have the same set of material properties (R_t, R_n, φ) and geometrical properties (Aspect, Slope, Height) as the slopes.

By varying the barrier’s design parameters, its adequacy, can be evaluated leading to the best possible design. An important capability offered is the design not only of vertical barriers but also of inclined barriers.

2.4 Three-Dimensional Visualization

The second section of the application (Fig. 1b) provides the 3D visualization of the simulated rockfalls. The ArcScene environment in which it is developed, allows also the management and the analysis of all the 3D spatial data provided and/or produced and users can create realistic scenes in which they can navigate and interact with the data.

In the same section, the 3D animation of the rockfalls (Fig. 4) can be generated providing even better perception of the phenomenon. The 3D animation shows the rock boulders falling along the calculated trajectories, in a strongly time-depended way (real time), thus users can have a very good perspective of the produced rockfalls, they can fully comprehend what happens and they can take all the necessary countermeasures. The 3D animations can also be exported as videos for further use and study.

2.5 Additional Tools

ROCKFALL ANALYSIS provides additional tools in order to help engineers to study rockfalls in a more quantitative way. For example, a tool can symbolize the simulated rockfalls based on the magnitude of the velocity that rock boulders have along their trajectory.

Another tool creates a 3D polygon shapefile with the sub area subjected to the simulated rockfalls. This area is defined by the Tin triangles traversed by the rockfalls. Data referred to the number of rockfalls traversing each triangle, the maximum velocity and the maximum height above ground surface that characterizes the set of the rockfalls traversing each triangle are provided in the shapefile's Attribute Table. As an alternative, these data can be presented in a table, i.e. without creating a shapefile.

3 IN SUPPORT OF DECISION MAKING

Rockfall hazard assessment is essential when designing infrastructure, settlements or facilities in mountainous areas. It helps greatly in land-planning, in the design of any technical work (roads, dams, etc.) and the design of countermeasures for protection purposes.

ROCKFALL ANALYSIS having all the aforementioned capabilities can strongly support design and decision making in any of the above situations. As far as landuse planning is concerned, the application is suited to ascertain rockfall hazard of areas of any extent. It can also be used for testing the safety of technical works and the efficiency of barriers already built or when designing new ones.

We need to note that to achieve a reliable rockfall hazard assessment, accurate input data are required. The DTM representing the topography of the study area must be as more detailed as possible. The data regarding the ground surface, the geological formations, the roads or the barriers must be validated by in situ tests during the execution of geological and geotechnical studies.

4 CASE STUDIES

Various case studies were performed in order to evaluate the application and the proposed simulation model (Kefalas, 2006. Charalambous, 2006). An area examined is the Selinari area in Crete, where a section of the new national road is very often subjected to rockfalls and landslides, resulting in road destruction and in reduced road safety. A number of rockfall tests were carried out (Kefalas, 2006); a sample of the simulations executed for those test is shown in Figures 1- 4.

5 DISCUSSION AND CONCLUSIONS

A new 3D rockfall simulation model was developed and incorporated in a GIS environment via the creation of the application ROCKFALL ANALYSIS which can simulate numerous spatially distributed 3D rockfall trajectories, providing users with a great amount of additional relevant spatial or non-spatial data.

Using this application in case studies, we concluded that rockfall hazard assessment and the design of countermeasures in mountainous areas can be supported by the application in a quite reliable way when data are accurate enough. Of course, ROCKFALL ANALYSIS represents an on-going effort and developments are possible. The user-interface can always be improved, yet the calculation aspect of the program is the one which must draw our attention. A more extended probabilistic analysis has to be implemented. Employing probability and statistics in rockfall analysis is an effective and acceptable method for overcoming difficulties caused by the great uncertainty which characterize the relevant parameters. Moreover, further investigation regarding the equations describing the movement of the boulder is also needed as they influence to a large extent the quality of the simulations.

More radical improvements might involve the implementation of a more dynamic model. In a first stage, the model might consider a simple shape of the boulder (a sphere, a cylinder or a disk) allowing for a more realistic simulation of the rebound and rolling phases of rockfalls. In a second stage, a complete 3D dynamic simulation of a boulder of any shape and size could be implemented.

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