Rockfall hazard and risk analysis in Sintra area

J. A. Almeida, C. N. Costa, J. C. Kullberg, H. S. Vargas
Centro de Investigação em Geociências Aplicadas, Faculdade de Ciências e Tecnologia,
Universidade Nova de Lisboa
Corresponding author: ja@fct.unl.pt

ABSTRACT : A rockfall is a geomorphologic process that occurs preferentially on sloping areas with large and unstable boulders. It is very important to provide hazard and risk maps due to rockfall as they are usually unexpected and can cause fatalities and several serious injuries to infrastructures and property.

This paper presents results of the development and implementation of a stochastic model in a Geographic Information Systems (GIS) that calculates sets of the most probable rockfall pathways for 188 sampled boulders potentially dangerous identified in "Monte da Lua", Sintra (a small town classified as world heritage by UNESCO). This study was promoted in the sequence of such an occurrence on the 29th of January 2002.

KEYWORDS : Rockfall, stochastic simulation, cellular automata, hazard map, risk map, GIS.

1. Introduction

The formulation of a physical or a mathematical model that accurately describes the most probable rockfall trajectory of a certain boulder or rock block constitutes a complex numerical problem as rockfall paths along a rocky incline is a function of numerous factors whose numeric formulation poses severe problems.

In general terms the variables used to describe the potential for movement initiation and dynamics can be subdivided in two groups: i) boulder properties: size, position, angular or rounded edges, volume or weight, centre of gravity; support and possible interaction with others; ii) contextual areas: terrain geometry, land use and energy dissipated.

In practical terms it is quite impossible to characterize accurately a rockfall path. The major difficulty in modelling the behaviour of a rockfall event is, therefore, to thoroughly characterize these variables, which is not a simple problem.

To avoid this complexity the basic idea of the proposed methodology is to generate multiple and equally probable trajectories for each boulder location dependent only from a reduced number of variables. All trajectories are then evaluated in terms of block potential to initiate and to continue the movement (hazard map) and intersection with edifications (risk map).

2. Rockfall trajectory simulation

2.1. Proposed algorithm for trajectory simulation

The main factor that controls the trajectory of a falling, sliding or rolling boulder is the geometry of the area (Dorren, 2003). In high steep slopes, the horizontal component of a boulder's movement can be high enough to allow the boulder to lose contact with the slope surface and move through free fall.

Another important trajectory controlling factor is the presence or absence of vegetation, soil or any kind of natural barriers or obstacles. Their presence controls the trajectory by decreasing the restitution coefficient (RC) and, not so often, the direction of a given pathway. The RC usually has high values on clean rock surfaces, and can also vary with lithology and weathering. For practical purposes, RC is presented as an angular value to be taken out of real slope angle.

There are other less important factors that interfere with the directions and length of the pathway, like boulder dimension and shape and its own weathering condition, which are difficult to model and mathematically difficult to relate to the boulder's movement. For this reason, the suggested methodology only makes use of slope geometry in the form of a digital elevation model (DEM) and of a calibrated RC.

The simulation of rockfall pathways is performed through a Monte Carlo simulation technique. This class of algorithms proposes the use of a regular mesh of identical cells in space, each of which being able to evolve within a finite number of states on each iteration. The dynamics of the system is determined by a set of transition rules, which control the change of the cell neighbourhood state from its actual state in time to the next (cellular automata model) (Banks *et al*, 1996).

2.2. Cell state change

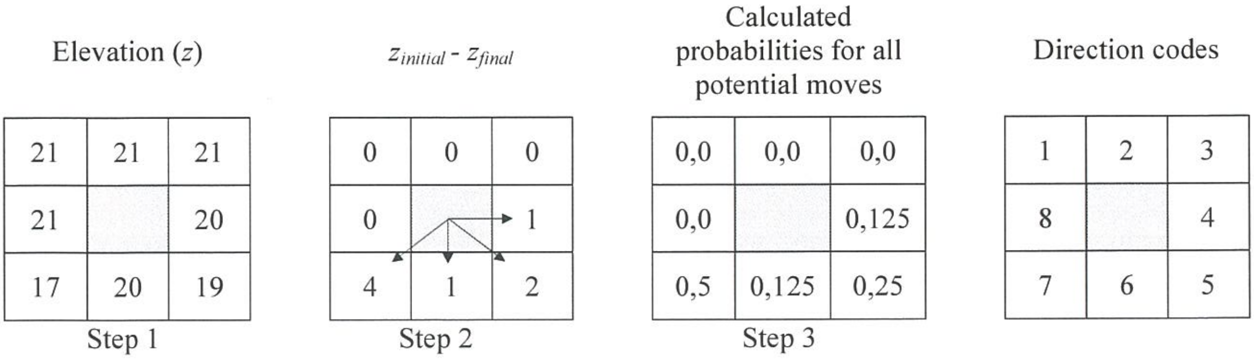
The representation of such a discretization of space is usually done by a matrix structure in a geographic information system (GIS) where, besides allowing the implementation of the above mentioned technique, each position in space is identifiable by its line and column indexes and the coordinate of the first cell and its dimensions. For each discretization of time t_k, each cell (ij) has to be characterized by one of the following conditions: i) contains the boulder; ii) contained the boulder in a previous iteration t_i, for $i < k$; iii) none of the above.

The movement of the boulder between cells is controlled by the slope angle and by its speed at the current location, not accounting for air resistance. The velocity increment ($v(t_{k+1}) - v(t_k)$) of a spherical object, in an $\boldsymbol{\alpha}$-inclined plane of length $\boldsymbol{l}$, with a friction coefficient $\boldsymbol{\tan\Phi}$ is given by (Giani, 1992):

$$v(t_{k+1}) = \sqrt{v(t)^2 + g.l.(\sin\alpha - \tan\Phi.\cos\alpha)} \qquad (g=9{,}8\,\mathrm{ms}^{-2}) \qquad (1)$$

If the friction angle is bigger than the slope angle then velocity decreases, if the slope angle is bigger than the friction angle there is an increase in velocity, if they are equal then there is conservation of movement.

If a boulder's velocity on a given cell is not zero it will pass onto a neighbouring cell. Theoretically all neighbouring cells with lower elevation are candidates to receive the boulder, with different probabilities as depending as on the slope gradient. These distinct probabilities allow the model to go on generating a trajectory (cell by cell) until the boulder comes to a stop. Figure 1 exemplifies the calculation of probabilities for a particular boulder position based on local and neighbouring elevations.



Elevation (z)

21	21	21
21		20
17	20	19

Step 1

$z_{initial} - z_{final}$

0	0	0
0		1
4	1	2

Step 2

Calculated probabilities for all potential moves

0,0	0,0	0,0
0,0		0,125
0,5	0,125	0,25

Step 3

Direction codes

1	2	3
8		4
7	6	5

Fig. 1. Determination of the boulder's probability to move to adjacent cells.

In this example, the central grey cell in figure 1 (all steps) represents the current position of a boulder. The probability distribution function (*pdf*) is generated from eight contiguous cells. From the local elevation model it's possible to calculate the local unevenness matrix (step 2), which results from the difference between the central cell's elevation and each of the neighbouring cells. Then, it's possible to calculate the local transition probability matrix (step 3), assuming a uniform law, which relates the unevenness matrix with the transition probability. The assumption of linear proportionality between unevenness and trajectory probability is used in several cellular automata models applied to risk phenomena simulation because they allow a very easy calibration for known crisis.

After determining local transition probability matrix, a random number between 0 and 1 is then generated according to a uniform law, which will correspond to a choice of direction – new cell – for the trajectory while in the new cell, the boulder's velocity is updated according to the distance travelled and to (1). If in a given iteration the boulder's velocity is equal to zero this means that the trajectory is over, the boulder has stopped and a new trajectory can be simulated.

2.3. Model Calibration

Within this cellular automata model, the boulder's trajectory geometry and length are characterized by two control parameters: the DEM and the friction angle $\boldsymbol{\Phi}$. The available DEM has a spatial resolution of 1 meter. In what concerns the adjustment of the friction angle, it was done by generating 1000 possible realizations of trajectories for a range of global friction angles (encompassing the real friction angle, the boulder's geometry, RC, etc) and comparing them to the known trajectory of the 29th of January. The realization that best described this trajectory derived from a simulation for a friction angle $\Phi = 21{,}5^{\circ}$.

According to Giani, 1992, a boulder's movement on a 40° angle slope is always performed in contact with the ground - free fall does not occur. If we associate this fact to the average slope angles at "Monte da Lua", we can validate the generalization of this methodology to the whole study area, for every boulder it contains, since they will only move by sliding or rolling.

3. Risk Analysis

After simulating the trajectories for the boulders in the study area considering $\Phi = 21{,}5^{\circ}$, potential risk was evaluated using a sequence of steps in GIS environment. These steps are:

- Simulate 1000 trajectories of equal probability for each boulder and average it;
- Identify and exclude erroneous trajectories – cells with hit count of 1 are zeroed;
- Determine individual potential trajectory basins;
- Summarize basin descriptor parameters: initial height, area (square meters), maximum length and width;
- Account for the number of potentially affected boulders in every trajectory basin;
- Analyse potential risk for each boulder: identifying, which trajectory basins are within 40 or 20 meters of existing buildings;
- Present a final hazard map containing the sum of all the trajectory basins and the potentially affected buildings.

The direct result of this methodology with $\Phi = 21{,}5^{\circ}$ was named the realistic scenario and, with it, we were able to identify problem carrying boulders (Figure 2) as this scenario is the geological hazard map due to boulder detachment and consequent mobilization.

Although this was the main goal of the methodology, the same number of simulations were made with Φ = 19,0°, to perform a sensitivity analysis. The result of this simulation was named the pessimistic scenario as the reduction of Φ extends trajectories (length) and identifies a greater number of boulders as representing a potential problem, although in lower hierarchical order in relation to the ones in the realistic scenario.

The realistic scenario results point out that 10 of a total of 188-catalogued boulders have some probability of reaching the 40-meter buffer and a total of 3 can reach the 20-meter buffer. Most of these are located in the northern section of the study area and represent real danger for the population.

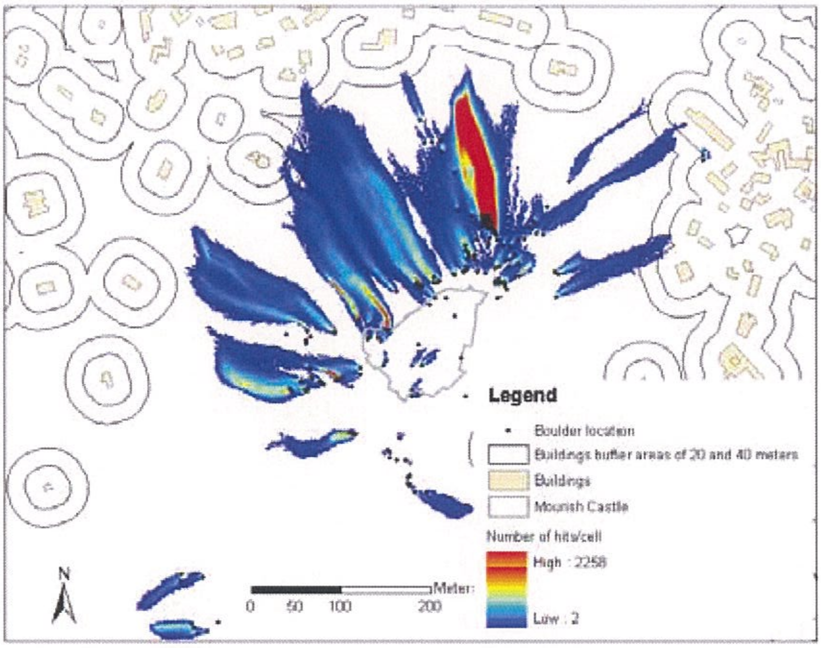


Fig. 2. Realistic scenario showing all boulder simulated trajectories.

4. Conclusions

The objective of this methodology was to present a geological hazard map due to boulder detachment and mobilization for Monte da Lua, Sintra. It consisted on the simulation of equally probable trajectory scenarios through the implementation of a stochastic model. Any such implementation, which depends on a reduced number of parameters (DEM and Φ), allows for the simulation of potential pathways. Allowing the friction coefficient to be adjusted, the result can be a more "realistic" or more "pessimistic" scenario, according to skilful criteria. The simulated trajectories can be used to propose mitigation measures on boulders, which represent greater danger for population or assets.

REFERENCES

Dorren, L., 2003. A review of rockfall mechanics and modelling approaches, Progress in Physical Geography 27,1, Arnold, 69-87, Lisbon.

Banks, J., Carson, J. & Nelson, B. R., 1996. Discrete event system simulation. Prentice Hall, Inc.

Giani, G. P., 1992. Rock Slope Stability Analysis, A. A. Balkema / Rotterdam / Brookfield.