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A New Software Tool for the Analysis of Rockfalls

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Rockfalls are gravitationally driven geomorphic processes that occur rapidly on steep rocky slopes. They can have disastrous effects on human activities and infrastructure and therefore constitute a significant natural hazard. However, due to the complex nature of the phenomenon, the available analysis methods incorporate assumptions that can lead to oversimplifications, since limited parameters are taken into account. This paper presents a new software tool for rockfall trajectory modeling. The software allows the user to choose the analysis method, selecting from: a) the lump-mass model; b) some recently proposed semi-empirical methods; and c) a new neural network algorithm that is trained with the data acquired from an extensive laboratory and field investigation, previously performed by the author (Asteriou, 2016). First, the software is presented and then the well-documented rockfall incident in Ponti, following the Mw=6.5 Lefkada earthquake in 2015, is briefly described and analysed with the software. The outcomes are commented and compared to the actual trajectory. Some interesting remarks on the reliability and accuracy of these methods are discussed.

Rockfall Software Structure

The software was developed in MatLab. The user interacts with the software through the Graphical User Interface (GUI) environment, resulting to a user-friendly application. In order to perform an analysis, the user must go through four stages; a) Model creation; b) Definition of parameters; c) Computation; and d) Interpretation. At the first stage, the user defines slope's geometry by importing an excel spreadsheet containing the vertex coordinates of each segment, input the vertex coordinates in the GUI environment or draw the slope manually with the cursor. Then, the detachment point is defined in the GUI manually or with the cursor. At the next stage, the user selects the analysis method and defines the parameters required by the selected analysis method in pop-up windows (such as: CORs, slope roughness, initial velocity and others). The computation (stage c) is performed according to what defined at the previous two stages. Finally, at the last stage, the trajectory is depicted and all necessary data (block velocity, kinetic energy, and rebound height) are available both graphically and in a tabular environment. After each stage has been completed the settings are automatically saved allowing to start-over the analysis in any stage and modify any parameter in order to assess different scenarios and compare the results.

Overview of the Available Analysis Methods

During a rockfall the block can travel through the air, roll or slide on the slope surface and impact onto the slope. While the block is travelling through the air, its motion is calculated by the ballistic trajectory equations. Following the projectile motion, the block will impact the slope and it will either rebound and revert to a new parabola, or slide on the slope surface. When the block is in contact with the slope, sliding or rolling is calculated according to Statham (1976). The rolling/sliding distance depends on the tangential velocity, the slope angle and the friction/roughness of the slope. The rebound can be assessed with one of the following methods:

- The lump-mass model, which is used in the majority of similar software due its simplicity. The response to the impact is described by the coefficients of restitution (CORs), which are assumed to be overall parameters that take into account all the characteristics of the impact. In practice, COR values are obtained by some indicative values that are provided as guidelines, which depend solely by the material that constitutes the slope surface.
- Some empirical models found in literature, which originate from back-analysis of real rockfall events (i.e. Wyllie, 2014) and from experimental testing (i.e. Giacomini *et al.*, 2012; Asteriou and Tsiambaos, 2018). These model are used to estimate the appropriate CORs taking into account more parameters, such as the impact velocity and angle, the material type and others.
- A neural network algorithm developed especially for this software that is based on the data acquired in Asteriou (2016). In general, a neural network is a computing model whose layered structure resembles the networked structure of neurons in the brain. A neural network learns from data, so it can be trained to forecast future events. The model used for the software is a deep learning multi-layered network that was trained by more than 3000 laboratory and field tests.

Analysis of the Ponti Rockfall

On 17 November 2015, an earthquake (Mw 6.5) struck the island of Lefkada and triggered a number of rockfalls. In Ponti village, a limestone block was detached at an elevation of 500m, rolled approximately for 250m, impacted 22 times on the slope and finally impacted a family residence, penetrated two brick walls and killed a person inside the house. The slope overhanging the residence has its peak at 600m and an average slope angle of approx. 40º and the house rests at an elevation of 130m. The block was nearly cubical with 1.4-m-sides and its volume was approximately $2m^3$.

The rock path and the impact points on the slope were identified by a field survey, performed using an unmanned aerial vehicle (UAV) with an ultrahigh definition (UHD) camera, which produced a high-resolution orthophoto and a digital terrain model (DTM) of the slope (Saroglou *et al.*, 2018). Figure 1 illustrates the plan view of the slope (top), its cross-section (bottom), and the actual trajectory impact points are depicted by the red vertical lines. Hereafter, a back-analysis of the Ponti event is presented using an example of each method available in the software.

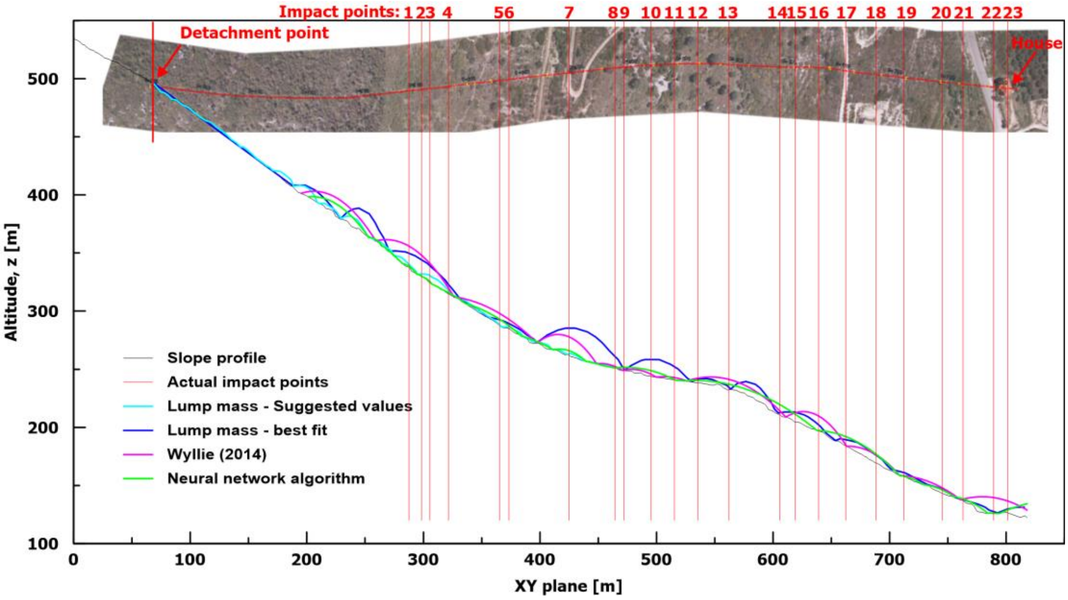

Figure 1. Plan view and cross section along the block's path.

First, the lump mass model is assessed using with the CORs suggested in literature (bedrock outcrops: n_{COR}=0.35 and t_{COR}=0.85). The falling rock primarily rolls on the slope and stops much earlier than its actual runout distance (Fig.1 – cyan path). In order to approach more closely the actual trajectory various CORs combinations were examined. The best match occurs with n_{COR}=0.60 and t_{COR}=0.85, which corresponds to bedrock (Fig.1 – blue path). 14 impacts occur instead of the actual 22, their positions significantly differ from the actual ones and the bounces are unrealistically high (up to ~25m) according to the observations of Volkwein *et al.* (2011).

Using the CORs estimated from the empirical model proposed by Wyllie (2014), the trajectory (Fig.1 - magenta line) consists of 12 impacts points, which are randomly positioned compared to the actual positions on the slope. However, the rebound heights are more realistic compared to the previous analysis presented, with a maximum bounce of ~12m.

Finally, the neural network algorithm provides the best estimate of the trajectory. It consists of 16 impacts with the slope, but again in different locations compared to the actual ones (Fig1. Green path). The trajectory is more shallow and realistic in terms of bounce heights, as the maximum rebound is ~6m.

Conclusions

In this study, a well-described rockfall event was analyzed with the aid of a newly developed software in order to assess various rockfall trajectory analysis methods. In addition, this software is equipped with a neural network algorithm that is trained with numerous experimental data. The results indicate that the classical lump-mass model approach, which is to estimate the CORs solely by the slope material and to consider them as constants, does not provide realistic paths and leads to excessive rebound heights. The trajectory is better appraised when CORs are calculated with semi-empirical models because CORs vary according to the impact conditions considered by the model. Finally, the neural network algorithm results to the most realistic path, since more parameters are involved to estimate CORs and in the same time the user has less parameters to choose. On the other hand, the main disadvantage of this neural network algorithm is its 'black box' nature, meaning that there is limited justification on how the output is reached and limiting understanding on the features that affected this output.

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