STUDY OF ROCKFALLS IN A QUARRY ENVIRONMENT PHYSICAL AND NUMERICAL EXPERIMENTS

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The study of rockfalls in quarries aims at a better understanding of the phenomenon and the improvement of safety conditions for employees. The later can be achieved through a correct identification and dimensioning of hazard zones related to rockfall activity. It is suggested that two different zones can be defined at the toe of a quarry slope and that these zones can be dimensioned according to rockfall associated values, concerning expected distances for runout and first impacts. These *characteristic* distances are influenced by several parameters such as size and form of falling rocks, surface roughness and geometry of the slope, rebound behaviour during impacts, all adding up to a relationship with a strongly random character. After observing and analyzing drop tests conducted on a granite quarry slope, we present results from efforts to calibrate and use an experimental stochastic *3D* code for rockfall numerical simulations.

Keywords: Rockfall, drop tests, numerical simulations in *3D*, hazard zoning

INTRODUCTION

Rockfalls are a common source of danger to employees at quarry sites. It has been suggested from previous research [1], that this kind of hazard could be managed in a preventive logic, by defining danger zones away from the toe of the slope. A first zone of highly destructive impact energy, can be derived from the *95* percentile of expected distance for first impacts (ID_{95}), signifying an area where danger exists even to operators of cabin featured-machinery, and no hauling activity should take place. A second zone of less destructive kinetic energy, can be defined from the *95* percentile of expected runout distance (RD_{95}), signifying an area where danger exists to employees protected through ordinary protective equipment. The dimensions of these zones can significantly vary from site to site and even at different locations of the same slope. This is a case where numerical simulations could be valuable, if only the aforementioned distances could be predicted within acceptable levels of reliability.

RESEARCH OBJECTIVES AND METHODS

Our main research objective is to test the performance and applicability of Wurf3D, an experimental rockfall code based on stochastic roughness and hyperbolic restitution factors. The code is scripted in PYTHON programming language and its theoretical framework is based upon the approach reported in [2]. In addition, a developed technique for the post-processing of rockfall simulation data, has enabled the accurate and fast calculation of intersection between rockfall trajectories and any given surface in *3D*. A *Ray - tracing* algorithm operating through tree - like hierarchical structures of spatial data, consists the core of the technique [3].

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Furthermore, a precise visualization of the terrain and of the rockfall trajectories, along with the possibility for an *on the model* measurement of distance, configure a virtual *3D* computational environment for the study of rockfalls (*Fig.1*). By performing drop tests in an active quarry, we have generated data for the calibration of the code. Through a combined study of physical experiments and numerical simulations, we assess rockfall behaviour and calculate characteristic distances which could assist in a correct selection and the optimal design of protective measures. It should also be possible to discuss on the limitations of the numerical approach, and how a careful consideration could improve the interpretation of the results.

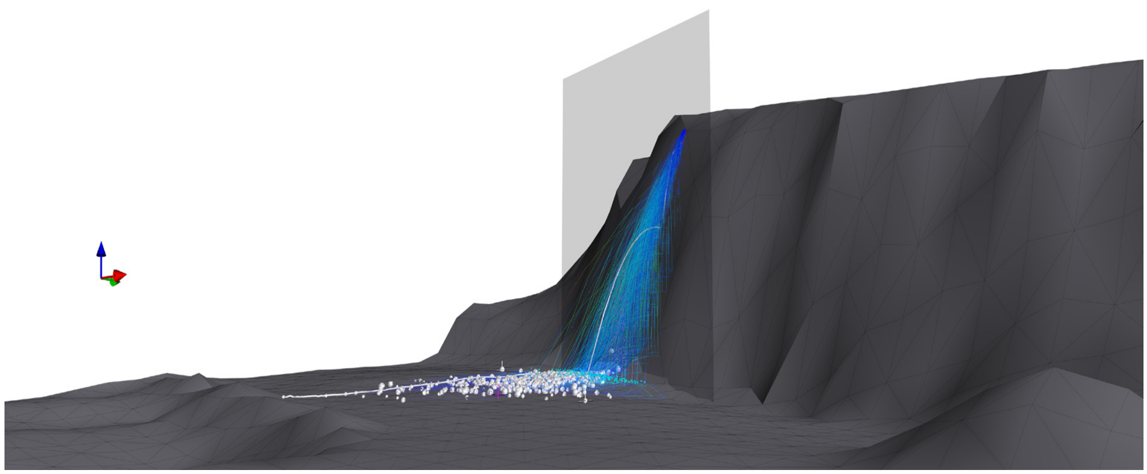

Fig. 1 Visualization of rockfall simulations and the creation of an interactive virtual environment using Wurf*3D*.

PHYSICAL EXPERIMENTS

A series of drop tests have been conducted on a granite slope in an active quarry located at Limberg, Maissau, in Austria. In total 64 boulders ranging from *4* to *4720* kg were tested in an experimental procedure similar to the one reported in [4], with two significant enhancements: the use of a digital crane-scale which has enabled direct measurements of boulder mass, and the capturing of rockfall motion through a camera equipped drone, recording in a 'birds-view' mode *(Fig.2)*. From drone photography it has also been possible to create a unified Digital Elevation Model of the quarry slope and its bench, through photogrammetric techniques. Gathered data has initially been explored with the aid of video analysis software, for a precise measurement of impact and runout distances as well as the lateral spreading of rockfall trajectories. The purpose of these tests was to assess and improve rockfall observation techniques and consequently produce a set of quality data, which could facilitate the calibration of a rockfall code. From the analysis of drop tests video data and the manual tracking of rockfall trajectories, it has been possible to measure impact and runout distances in a consistent way, with excellent agreement to on-site registered measurements.

Fig. 2 Drop tests in a granite quarry at Limberg, Lower Austria. Geological unit of the Bohemian Massif. Monitoring with the aid of a video recording drone.

SIMULATION PARAMETERS

The principle of the numerical approach is to simplify the mathematical description of rockfall, following a 'hybrid' lumped mass scheme, and to account for naturally observed random behaviour, through a limited number of stochastic parameters that could be possibly calibrated against actual drop tests. Goldsmith's impact model is being used for the mathematical treatment of impacts and the calculation of translational and rotational rebound velocities [2]. Two input parameters, termed as roughness coefficients C_θ , $C\varphi$ are the solely stochastic elements of the simulation. They are controlling the extent of a random change in the inclination of the impact surface in longitudinal and transverse direction respectively, for each impact configuration. A further two parameters, representing energy levels, are marking a 'reference deformation energy' in normal and tangential direction (E_n, E_t) which is used to control the hyperbolic functions [5] relating normal and tangential restitutions factors (K_n, K_t) to the normal component of translation incident velocity and the boulder equivalent radius. Obtaining correct values for the aforementioned parameters is the purpose of the calibration procedure.

CALIBRATION APPROACH AND ITS RESULTS

In terms of programming, it has been possible to automate the calibration process. The numerical code through its calibration module, can be executed several times, being initialized for each run, with its key parameters randomly varied within a user specified range of values. In such a way, model behaviour could be explored in a broad range, by creating a large number of random combinations for model initialization. The accuracy of each simulation can be assessed by computing the root mean square (*RMS*) error between simulated and observed values, for selected parameters. Results from a Kolmogorov – Smirnov test, which is a statistical method to compare two different Cumulative Distribution Functions (*CDFs*), have proved to be useful for the calibration and in agreement with the *RMS* method (*Fig.3*).

The calibration process has indicated that model response is very sensitive to the roughness coefficients C_θ, C_φ. In general, it has been possible to arrive at a set of parameters that could produce simulations with higher than *1m* of accuracy when the *50* and *95* percentiles for both runout and impact simulated distances were to be compared against observations. At the same time, other rockfall characteristics, measured in drop tests, such as the maximum lateral spreading of the first impact points as well as the average lateral spreading of end boulder positions, could also be simulated with fine accuracy.

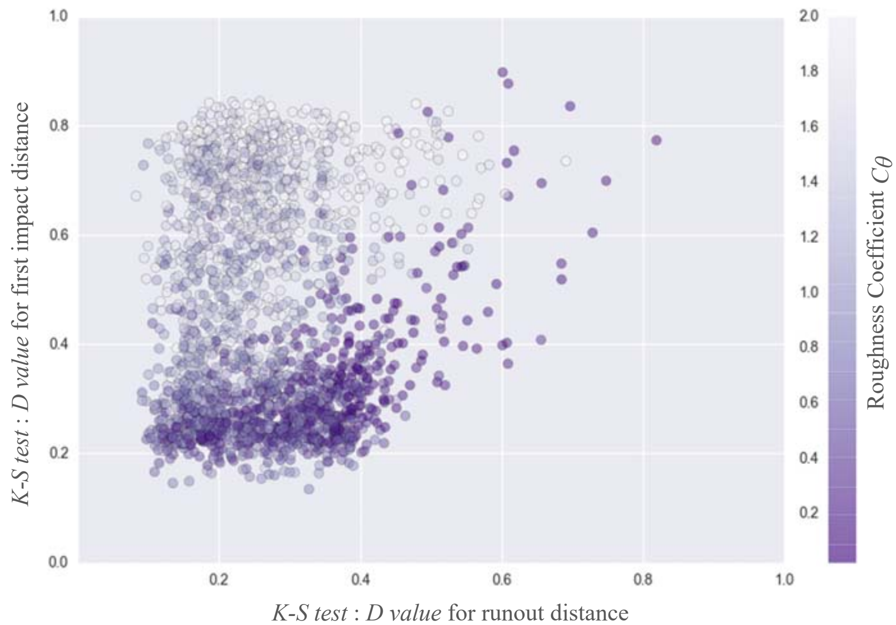

Fig. 3 Typical results from a Kolmogorov - Smirnov statistical test. Comparison of observed against simulated distributions, after a broad calibration procedure through 2000 random realizations.

CONCLUSIONS

Numerical simulations can assist in a better understanding of rockfall behaviour at quarries. Results, generated and interpreted by experts, can be used as to improve safety conditions and to bring site operation in conformity with relevant safety regulations. Data from advanced drop tests has been utilized for the calibration of a stochastic rockfall code in *3D*. Precise visualization and new methods for the post processing of numerical simulations, provide with the possibility for a robust evaluation of *characteristic* rockfall-related distances, within an interactive virtual environment.

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