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Stochastic analysis of rock fall dynamics on quarry slopes

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ABSTRACT

In order to study rock fall dynamics, a research project conducted by the Vienna University of Technology and the Austrian Central Labour Inspectorate (Federal Ministry of Labour, Social Affairs and Consumer Protection), 589 full-scale drop tests were carried out in different quarries, recording key parameters of the rock fall trajectories. Similar drop tests were conducted by a team from the University of British Columbia and the B.C. Ministry of Transportation and Highways at a quarry site in British Columbia, Canada. In this paper, detailed results of 277 tests at three sites in Austria and 34 tests at the site in Canada are described. The tests involved a total of 311 boulders ranging from 0.18 to 1.8 m in diameter and from 0.009 to 8.1 Mg in mass. The geology of the different sites included strong rock belonging to igneous, metamorphic and volcanic types. The results of the tests are compared to computer analyses conducted with a new dynamic model, using a single set of parameters for all the sites. In general, reasonable stochastic approximations of the rock fall trajectories have been obtained in all dimensions, including runout, bounce heights and velocities. The approximations are compared to the measured data in terms of median, 95% and maximum values. The results of the comparisons indicate that approximate first-order predictions, using a single set of input parameters, are possible and can be used to aid practical hazard and risk assessment.

1. Introduction

Falling blocks and rock mass falls are a common cause of accidents in quarries and open pit mines (Fig. 1). In Austria, a new regulation concerning health and safety at work plants for quarries, titled “Tagbauarbeitenverordnung – TAV”, came into force in 2011. This regulation includes the requirement of specific risk assessment of geologic hazards with the purpose to determine areas in which danger of rock fall exists. To accurately assess the risk, one must first accurately determine the hazard. The distance from the toes of the slopes affected by rock falls, as well as the bounce heights within these zones, is often assessed incorrectly, leading to the hazards from these events being estimated wrongly. The dimensions required for assessment of hazards to personnel and equipment are defined in Fig. 2. They include the distance from the slope toe to the location of the first impact on the quarry floor (“first impact distance”, *ID*) and the “runout distance” (*RD*), measured from the toe of the face to the point of deposition of the boulder. The size and form of the blocks, the height of the fall, the slope geometry, the surface roughness and the damping parameters (factors of restitution) of the ground control the mechanism of the fall (sliding, rolling, bouncing and falling) and cause different impact and runout distances. Similar safety regulations exist in Canada, although to date, quantitative risk analysis is not required for quarrying or mining operations.

The purpose of this paper is to present results of full-scale tests of rock falls at several Austrian and Canadian quarries and to evaluate predictions of the basic hazard dimensions *ID* and *RD* using a new computer model of rock fall dynamics.

2. Full scale testing at quarry sites

2.1. Test procedure

A total of 10 different sites with several rock types (calcareous rocks, granite, basaltic rock and iron ore, etc.) were investigated, nine of which are in Austria and one in British Columbia, Canada. A total of 589 boulders were released individually on fourteen different slopes with slope heights between 9 and 75 m (Fig. 3). The mean slope angles of all the quarry faces ranged from 53° to 71°. The complete data set was used for derivation of the empirical relationships presented in this section. Seven (311 tests) of the fourteen investigated slopes (six slopes in three quarries in Austria

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Fig. 1. Photo of a rock fall accident at a quarry in Austria.

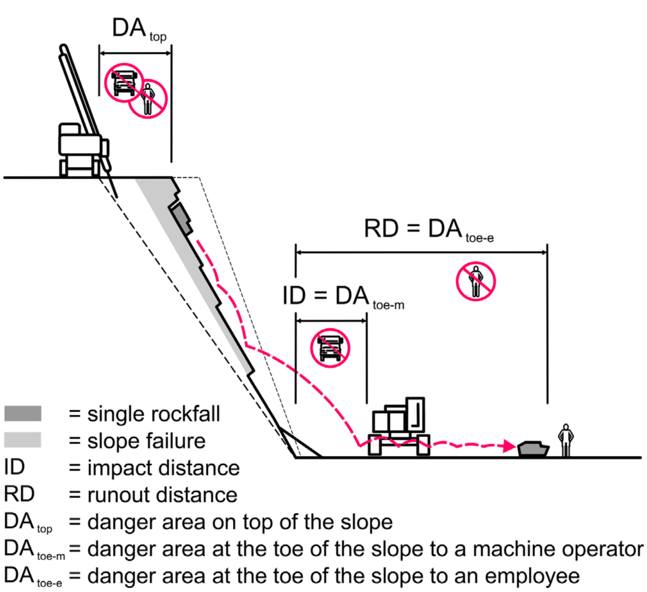

Fig. 2. Danger areas associated with a quarry face.[1]

and one site in Canada) were selected for detailed back-analysis. The reason for this is that a metric 3D-image was available for the six selected Austrian slopes. The 3D-images gave us the ability to generate representative cross sections for the analysis, and to investigate the influence of the degree of detail of the modeled slope

Fig. 3. Rock fall drop tests in progress at the Klöch Quarry in Austria.

geometries on the calculated hazard distances. The 3D-image was created using the ShapeMetriX3D system (3G Software & Measurement GmbH, Austria), which is based on the principles of classical photogrammetry.

During all the experiments in the Austrian quarries (Klöch, Wanko, Erzberg, Pauliberg, Preg, Loja, Bad Deutsch Altenburg, Mannersdorf & Dürnbach) the protocol was identical. First, the volume of the boulder to be thrown was estimated by measuring the three dominant boulder axes and recorded. The mass of the boulders varied from 0.002 Mg up to 44 Mg (16 m^3). An excavator (with an average operating weight of 35–55 t) was used to move the prepared boulders (numbered and placed at the crest of the slope) gently over the edge of the slope. At the end of each experiment, the stopping points of the boulders were measured. The impact distances were estimated by video analyses. After every five throws, the boulders deposited on the quarry floor were removed by a wheel-loader, in order to prevent boulder interaction during the following throws. Rock fall trajectories were filmed using two digital cameras, installed at the top and near the toe of the slope.

In the Canadian quarry (Nicolum), the falling fragments were filmed by two analog video cameras positioned on the quarry floor giving different perspectives on the trajectories (Fig. 4). A total of 34 trajectories were recorded for the Nicolum quarry tests. The blocks used ranged in mass from 0.03 Mg to 3.04 Mg (0.011 to 1.2 m^3). The trajectory of each boulder was traced on the videos with reference to survey marks on the slope, so that the geometric position and timing of each impact could be recorded. This allows estimation of flight heights using ballistic calculations. Runout of the boulders was not measured at Nicolum, because there was an experimental rock fence at the foot of the slope, which stopped most of the rocks. The fence impact parameters are not reported in this paper.

2.2. Summary of field test results

One objective of the Austrian component of the research project was to document the runout distance as a function of the slope height. A summary histogram of all measured runout distances, RD, normalized by slope height, is shown in Fig. 5b and fitted by the Weibull and log-normal distributions. The log-normal distribution shows the better fit, with a Kolmogorov–Smirnov test statistic of 0.037 and p-coefficient of 0.372, indicating a good fit and a high confidence in the fit. Similarly, the summary of height-normalized impact distances, ID, can be approximated by the log-normal function, as shown in Fig. 5a. These summary plots and