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Statistical evaluation of rockfall energy ranges for different geological settings of New South Wales, Australia

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ABSTRACT

Structures used in rockfall protection are designed on the basis of the expected impact energy. This quantity is usually assessed using commercial lumped mass models that stochastically predict possible block trajectories on a given slope. In New South Wales, Australia, it is estimated that rockfall hazard involves values of energy which are much lower than those in Europe, Canada or the USA. However, this view has not been supported by any systematic study across the whole state. Such a study is presented in this paper. It applies to the five geological situations that are the most prone to rockfall in eastern Australia. Previous experimental findings, relating to block size distribution or restitution coefficients (reviewed herein), have been used to perform this statistical analysis. A newly formulated lumped mass program, which incorporates a relationship between the normal restitution coefficient and the impact angle, allows the adoption of normal restitution coefficients in excess of unity for impact angles lower than 30°. The results confirm that in three out of the five geological situations, the 95th percentile of impact energy is lower than 200 kJ, and less than 2000 kJ for the other two situations.

1. Introduction

As for any engineered structure, the design of rockfall protection structures requires the determination of a design load: in this situation it is the impact energy which must be withstood. Prediction is usually achieved using numerical codes such as CRSP (Jones et al., 2000) or Rocfall (Stevens, 1998) that predict the possible trajectories of a large number of boulders for a given slope in a stochastic manner. These codes provide the statistical distribution of total energy of the blocks at a specified location along the slope. Energy prediction is usually a one-off task, carried out for a specific slope where rockfall has been identified as a possible hazard (Pierson and Van Vickle, 1993; Fell et al., 2008). In some cases where attention is focused on hazard mapping, larger areas are considered (Ayala et al., 2003; Chau et al., 2003; Cascini et al., 2005; Mazengarb, 2005; Chiessi et al., 2010) but the statistical assessment of impact energy is seldom applied to whole geological areas.

It is clearly recognised that the magnitude of rockfall energy is a function of the geology of the area, since this affects the shape and steepness of slopes, the sizes and shapes of boulders and the material constituting the slopes (Ritchie, 1963; Bozzolo and Pamini, 1986; Azzoni et al., 1992; Giani, 1992; Azzoni and de Freitas, 1995; Giani et al., 2004; Vandewater et al., 2005). Rockfall energies can reach very high values, as is evident in the recent development of high capacity barrier systems: 5000 kJ (Trad et al., 2011), 7000 kJ (Maccaferri, 2007) and 8000 kJ (Geobrugg, 2011). However, in many places worldwide, the rockfall hazard involves much lower values of energy. Muraishi et al. (2005) surveyed 607 rockfall events in Japan, of which 68% involved energies less than 100 kJ. Similarly, there are regions of Australia where a rockfall hazard does exist but involves relatively low levels of energy (Young, 1983; Gordon, 1999; Dahlhaus and Miner, 2000; Dutton and Stocker, 2001; Kotze, 2007; Hunter et al., 2011). This is particularly the case in New South Wales, where the nature of the geological environments is inherently different from the mountainous areas of Europe or Northern America. Although this fact is recognised (for example, by the roads authority; Buzzi et al., in press), the range of possible impact energies in New South Wales has never been quantified. Consequently, the applicability of proprietary systems, which have been developed for other geographical regions, to Australian rockfall hazard situations is unclear.

The purpose of this paper is to quantify the likely rockfall hazard characteristics which are typical of the major geological regions of New South Wales. These can be used to develop a series of standard protection structure designs which are generally suitable for particular geological settings. Rockfall analyses have been performed for a large number of characteristic slopes, coming from five different geological settings prone to rockfall in New South Wales, using a statistical approach. Experimental data, gathered from previous studies in these settings (Spadari et al., 2011; Fityus et al., 2012) were used as inputs for a new lumped mass numerical program, developed for the purpose of the study. This program is based on the same physical principles as most other lumped mass models, but incorporates the possibility of using restitution coefficients greater than unity and defines a relationship between k_n and the impact angle. It is shown that these features prove

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necessary to achieve meaningful results in the environments tested. As a result of the study, statistical distributions of the likely impact energy have been produced for five different geological situations which are prone to rockfall hazards. Such statistical data are useful for the pre-design of a range of standard interception structures, on the basis of the accepted level of risk in a specific geological setting. They also quantify the difference in the rockfall hazard between New South Wales, Australia, and other locations where significant rockfall developments have previously taken place (such as Europe, Canada and the USA).

2. Characteristics of rockfall prone settings in New South Wales

2.1. Definition of the relevant geological situations

As indicated by Branagan and Packham (1967), the East Coast of New South Wales, along the Great Dividing Range, is where the rockfall hazard is the most significant. This is mostly due to the geomorphological characteristics of the region: hilly to mountainous areas, moderate to steep slopes, and the presence of rocky outcrops and rock debris. In contrast, the inland regions are generally flatter and less problematic in terms of rockfall. In addition, the East Coast has seen a progressive urbanization over the past decades, which has increased the exposure to the rockfall risk.

In this study, four distinct geological settings have been proposed on the basis of characteristics that are relevant to the rockfall issue. These are outlined on the simplified geological map in Fig. 1, and consist of:

- The Sydney Basin Sandstones (denoted SBS), of predominantly Triassic age, comprising thickly-bedded sandstones in a relatively undeformed sedimentary basin setting. These mostly occur as the Narrabeen and Hawkesbury sandstones (Herbert and Helby, 1980);
- The Palaeozoic Fold Belts (Lachlan and New England), comprising sequences of sedimentary and volcanic rocks, affected by moderate tectonic deformation (Branagan and Packham, 1967). From a rockfall perspective, two significant and distinctive lithologies, representing two different geological situations, are recognised: the Fold Belt Sandstones (denoted FBS), and the Fold Belt Volcanics (denoted FBV). These each occur as tilted, moderately to thickly bedded units, but with distinctly different fracture and weathering characteristics. They can be mapped at the local scale but cannot be distinguished on the scale of a regional map (Figure 1);
- Tertiary flood basalts (denoted B), in horizontally layered flows, which characteristically occur as capping layers along the Great Dividing Range (Johnson et al., 1989);
- Granites (felsic granitoids, denoted G), which are mostly of Palaeozoic or early Triassic age and which occur as intrusions throughout the Palaeozoic fold belts. (Johnson, 2004).

This study will focus on the five different situations presented above: FBS, FBV, G, B and SBS, noting that two different situations are recognised in the Palaeozoic fold belt setting. Note that it is not the purpose of this paper to discuss the geology of these settings.

Although the different settings differ in terms of slope geometry, slope material, restitution coefficients, block material and block dimensions, it has been found that the distribution of block size is the main difference between the settings (see Section 2.2). This characteristic significantly affects the outcomes in terms of impact energy, as is shown in the Results section. The other characteristics all have a minor influence: all the slopes tested were slightly vegetated and covered with sparse debris yielding similar values of restitution coefficients (Spadari et al., 2011). In addition, the natural variability of the

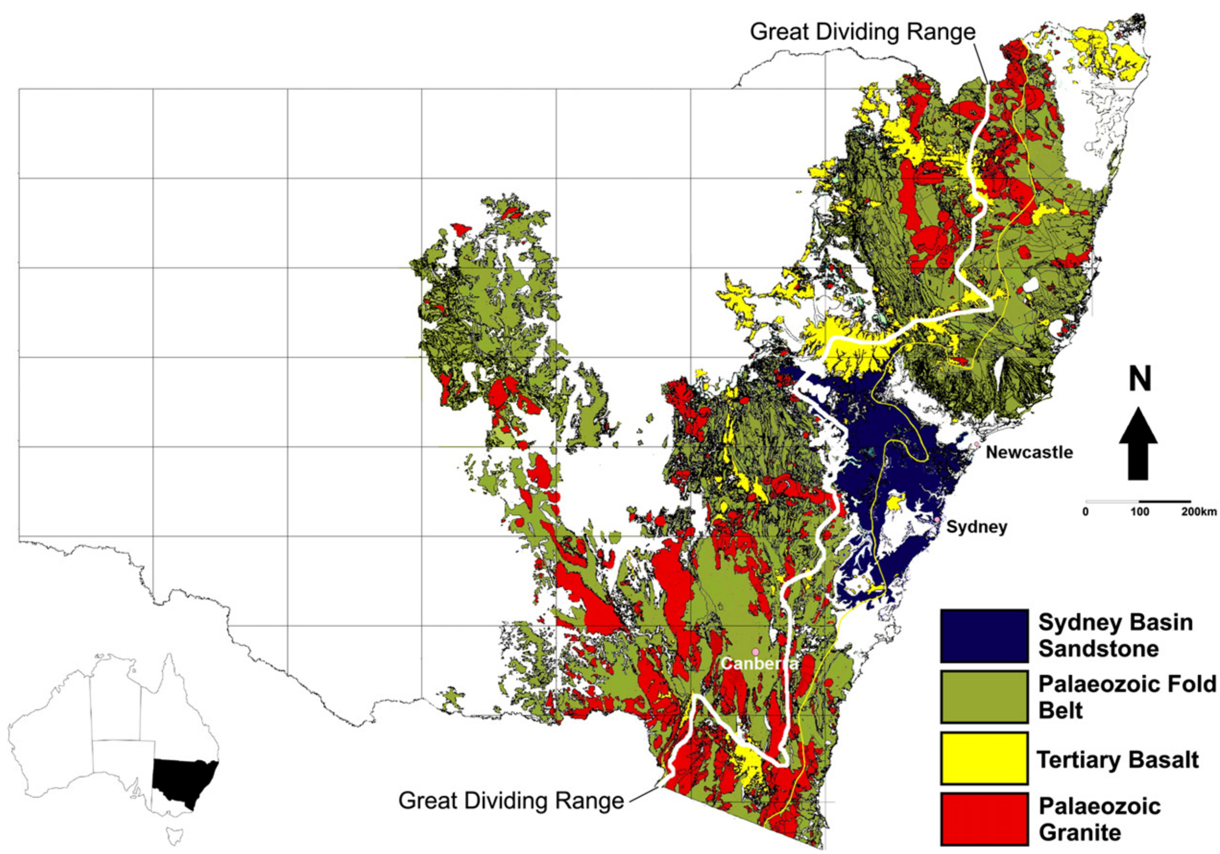

Fig. 1. Excerpt from the geological map of New South Wales, highlighting the geological settings relevant to rockfall. The Palaeozoic Fold Belt setting includes sandstones and volcanics. Adapted from Fityus et al. (2012).