Engineering Geology 162 (2013) 43–52

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

The significance of geology for the morphology of potentially unstable rocks

S.G. Fityus *, A. Giacomini, O. Buzzi

Centre for Geotechnical and Materials Modelling, The University of Newcastle, Callaghan, NSW, Australia

ARTICLE INFO

Article history:
Received 16 April 2012
Received in revised form 12 April 2013
Accepted 19 May 2013
Available online 24 May 2013

Keywords:
Rockfall hazard
Rock fragment
Block
Size
Shape
Geology

ABSTRACT

From a consideration of the concepts of geological weathering and structure, it can be expected that rockfall hazards should be characteristically different in different geological environments. This paper tests this idea by looking at the geometric characteristics of rock fragments formed on natural slopes in four different geological environments in Eastern Australia, where rockfall phenomena are often characterised by rolling of pre-detached debris. By measuring the three principle dimensions and making a systematic assessment of the shape characteristics of samples of rock debris in significant geological environments, it is found that the distributions of size and shape for the surface debris are statistically different. From the results, it is shown that the size and shape of debris is directly controlled by the rock type, its weathering characteristics and the structure of the parent rock mass. The severity of rockfall hazards is shown to be relatively lower in areas of Tertiary basalt, as the size of rolling fragments is limited by closely spaced fracturing inherited from its formation and the tendency to deteriorate further as it weathers deeply and rapidly. It is also lower in areas of Palaeozoic volcanics, since these tend to produce relatively angular fragments with higher proportions of fragments that are inherently more resistant to rolling. By contrast, thickly bedded sandstones form larger blocks with a larger proportion of shapes that are more prone to rolling. The size distribution of fragments is shown to be well approximated by a log-normal statistical distribution, and using the data provided in this study, it is possible to generate the size and shape data needed to undertake a stochastic assessment of rockfall trajectories in different geological environments.

1. Introduction

Hazards posed by falling rocks are an important issue to be addressed by engineers and managers in many parts of the world. Not surprisingly, the motion and fate of falling rocks have been the subjects of many studies throughout the applied geosciences literature (e.g. Broili, 1973; Budetta and Santo, 1994; Agliardi and Crosta, 2003; Guzzetti et al., 2003; Giani et al., 2004).

Much attention to date has focussed on rockfall environments where the hazards are severe such as in alpine areas, where large blocks of rocks, or sections of rock mass can detach from high cliffs in steep, topographically-immature valleys (Azzoni et al., 1995). In such environments Paronuzzi (2009) observes that “most single blocks move downslope by parabolic rebounds in the air”. However, the significance of rockfall extends well beyond this, to the widespread occurrence of undulating/rolling topography, where already-detached rocks on more moderate slopes can pose a potential hazard through motions dominated by “rolling”.

The particular characteristics of motion of a “falling” rock depend strongly upon the steepness of the slope (Ritchie, 1963; Dorren, 2003). However, whether a rock can fall (fall, bounce and/or roll) in a sustainable way, and its resultant trajectory, depends on many factors. These include characteristics of the slope (roughness, steepness, material) and characteristics of the block (shape, size, substance (strength, resilience)) (Ritchie, 1963; Pfeiffer and Bowen, 1989; Giani, 1992; Azzoni et al., 1995; Agliardi and Crosta, 2003). This paper considers the relationship between geological origin and the size and shape of rocks that present as hazards on slopes in regions of moderate topographic expression.

2. Size and shape of rock fragments

2.1. The significance of size and shape

Whilst slope morphology and steepness exert major controls over whether motions are dominated by bouncing or rolling (Ritchie, 1963), the size and shape of blocks significantly affect the precise trajectories (Pfeiffer and Bowen, 1989), and the severity of associated risks to life and property. It is readily apparent that larger rocks pose greater hazards, all other things being equal. The size of a mobilised rock, or more precisely, the size of the rock relative to the slope surface roughness (Pfeiffer and Bowen, 1989) also controls

* Corresponding author at: Centre for Geotechnical and Materials Modelling, The School of Engineering, The University of Newcastle, Callaghan 2308, Australia. Tel.: +61 2 4921 5294; fax: +61 2 4921 6691.
E-mail address: Stephen.Fityus@newcastle.edu.au (S.G. Fityus).

0013-7952/$ – see front matter.
http://dx.doi.org/10.1016/j.enggeo.2013.05.007

the likelihood that its motion will or will not be sustained (Dorren, 2003). Also, as larger rocks have greater physical size and greater momentum, they are less likely to lodge amongst irregularities on a slope of given roughness (Ritchie, 1963).

The shape of blocks has a significant effect on the ease with which motion can be initiated: in the context of pre-detached debris on slopes, more-angular blocks with a smaller number of flat faces are inherently more stable than rounded blocks. The shape of blocks also affects the extent to which rolling will be sustained, and the randomness of the motions generated during impact (Kobayashi et al., 1990). In particular, as the angularity of blocks increases, the tendency for transitions between translational and rotational motions increases (Pfeiffer and Bowen, 1989).

Information on the size and shape of falling rocks is important for most methods of rockfall motion prediction, to greater or lesser extents. Azzoni et al. (1995) observes that to carry out correct analysis of in situ tests, it is crucial to determine, as carefully as possible, the geological and geomechanical characteristics of the falling blocks and the slope, and that the characteristics of motion after impact are heavily conditioned by the block's shape. Bourrier (2009) considers that trajectographic modelling remains highly speculative since the information available on the mechanical and geometrical properties of the soil is not sufficient. Dorren (2006) concludes that for further improvement of rock fall simulation on different slope types, more quantitative data is required on rock shape as well as the rock size.

Advances in computer hardware and software now make it possible to perform complex dynamic analyses taking actual block shape into account (Maeda, 2009; Lisjak and Grasselli, 2010). Agliardi and Crosta (2003) considers that the accuracy and precision in the description of the block shape and mechanical properties is usually so low that complete dynamic analysis is prone to sum up an unacceptable amount of error. This clearly points to a need to improve our understanding of rock shape in rockfall environments.

2.2. Our understanding of size and shape

There is surprisingly little in the scientific literature to assist our understanding of the likely size and shape of potentially falling rocks in different geomorphic environments. It has been recognised that the outcomes of fragmentation processes are often populations of fragments with log-normal size distribution, but these are not contextually specific (Turcotte, 1997). For rocks that might detach from exposed rock masses, there are texts on structural geology that present general information on rock mass structure, with reference to different geological settings (e.g. Suppe, 1985), and works on rock mass structure characterisation (e.g. Kalenchuk et al., 2006). There are also papers, which for a variety of purposes, describe case studies which report site specific data that relates fragment size to rock mass structure (Agliardi and Crosta, 2003; Latham et al., 2006; Topal et al., 2007; Sturzenegger et al., 2011), but whilst they might describe the hazard of rocks that might detach from cliffs, these are not directly applicable to the characteristics of detached rock debris on hill slopes.

For rocks that occur as pre-detached fragments in geological environments, existing information on size and shape is rare. Some consideration has been given to the size and shape of fragments in natural sedimentary environments such as rivers and beaches (Sneed and Folk, 1958; Dobkins and Folk, 1970; Miura et al., 1998) but its relevance to the rockfall problem is small. Some consideration has been given also to rock fragments that are occurring as residuum or debris in soils, from agricultural and landform evolution (soil loss) perspectives (Flint and Childs, 1984; Le Roux and Vrahimis, 1987; Parsons and Abrahams, 1987; Poesen and Lavee, 1994a, 1994b; Simanton and Toy, 1994; Ugolini et al., 1996; Poesen et al., 1998) but its relevance is also limited.

2.3. Basis and approach for this study

The shape and size of rock debris is a function of the rock type and the processes that have caused it to become a fragment in its current situation. More specifically, the morphology of rock fragments is determined by the rock material and its fabric, the primary structures imparted to it during its formation, the additional structures imparted to by subsequent tectonic processes (the so-called "tectonic imprint"; Coe and Harp, 2007), the processes responsible for its detachment from the rock mass and the weathering environments it has been exposed to (Lindholm, 1987).

The first four of these factors collectively determine the rock mass structure. They are related through the geological setting (past and present) in which the rocks occur, and they are largely independent of where in the world the rocks occur. For example, undeformed sedimentary basins typically exhibit a fundamental jointing system (Mandl, 2005) comprising systematic tension jointing which is perpendicular to bedding (Hobbs, 1967; Narr and Suppe, 1991). These commonly comprise 2 sets of orthogonal joints (Mandl, 2005) with a spacing which is similar to the thickness of the bed they are developed in (Narr and Suppe, 1991). As a consequence, beds of sandstone and conglomerate in undeformed sedimentary basins tend to comprise relatively equi-dimensional orthogonal (cubic) prisms in the rock mass.

By contrast, mildly deformed sedimentary basins (fold belts) exhibit additional tectonic joint sets (e.g., Coe and Harp, 2007). These include cross joints (Bai et al., 2002), strike joints (Engelder and Geiser, 1980) and oblique joints (Price, 1959). As many as 5 or 6 joint sets may coexist. Sedimentary beds in these environments, which are usually inclined, tend to comprise more rectangular and/or rhombohedral and triangular prisms in the rock mass than their un-deformed counterparts.

Volcanic and ignimbritic units have a fundamental jointing system of cooling/shrinkage joints, which are generally oriented perpendicular to the bed surfaces and which may display a columnar arrangement, developed to greater or lesser extents (Suppe, 1985; Spry, 1961; Fityus et al., 2010). Undeformed volcanic units (e.g., Tertiary flood basalts) typically comprise polygonal prismatic blocks in the rock mass. Volcanic units in deformed environments (e.g., within folded fore-arc basin sequences) may be overprinted by tectonic joints, making the blocks within the rock mass smaller, less prismatic, and consequently, more irregular.

The processes which produce large debris from an intact rock mass are mostly environmentally controlled. They include detachment, weathering and possibly erosion processes, though not necessarily in this order. The variety of specific processes within these general categories varies greatly from alpine to tropical environments (Robinson and Williams, 1994). Invariably, water, temperature and salts play important roles, but to differing extents (Hall, 1999; Evans, 1970; Doornkamp and Ibrahim, 1990). A common factor, however, is the occurrence of these processes in the ground/soil and, to some extent conditions in the ground are less variable than on the surface.

It is the premise of this work that the morphological characteristics of blocks formed from similar basic geologies, in similar physical environments, will have similar and characteristic size and shape distributions. Hence, it is possible to characterise the size and shape distributions of potentially unstable debris for general geological settings, and to use this information in any region where similar geological and environmental conditions prevail.

This premise is tested here in the context of rock fragments derived from a variety of common geological settings, encountered in the physical environment of New South Wales (NSW) in eastern Australia, where the management of hazards posed by detached rock debris on slopes is a significant and resource-intensive issue. To test the premise, we have surveyed populations of loose rocks, occurring naturally on "undisturbed" slopes in geologically different regions, to determine their shape, dimensions and basic morphology. The statistics derived from the survey data are compared to determine if there is a characteristic difference between the rocks that would pose hazards in different geological environments.