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ABSTRACT: The term rockfall is often used ambiguously to describe various mass movement processes. Here we propose more precise terminology based on the physical nature of the moving mass, differentiating between two distinct types of rockfall: fragmental rockfall and rock mass fall. For both rockfall types, the current knowledge of the mechanisms controlling propagation of the mass movement are described, showing how these mechanisms can be simulated with different modelling approaches. However, we point out that almost no development has been realized concerning dynamic behaviour of the transitional processes between these two end-member rockfall types. Some simplified means of dealing with these complications are suggested, but we emphasize that a considerable amount of fundamental methodological development remains necessary.

KEYWORDS: modelling; Fahrboeschung; granular flow; fragmental rockfall; energy line

Rockfall Terminology

Rockfall (or rock fall) is a type of landslide, during which a volume of rock detaches from a steep slope along discontinuities such as fractures, joints, and bedding planes, and moves down a steep slope by free fall, bouncing, and rolling [paraphrased from Varnes (1978) and Whittow (1984)]. In most cases, the initial movement (‘detachment’) occurs by sliding or rotation (toppling), or by tensile, bending or buckling failure. The detached volume may remain as a single fragment, or may sooner or later disintegrate into several fragments, or even into a granular mass. As recognized by Varnes (1978), fall of rock fragments can also originate from bouldery regolith (‘debris fall’). The term ‘boulder fall’ is used in regions with widespread residual soil cover on slopes, to describe roll out of corestones loosened from saprolite (ERM, 1998).

Rockfall events are generally classified by practitioners depending on the total volume propagating down a slope. Significant differences exist between classifications used in different countries. German literature from the Alpine countries recognizes *steinschlag* for detachment of fragments less than 0·5 m in diameter, *blockschlag* for larger fragments, *felssturz* for detachments of more than 100 m^3 and *bergsturz* for major rock avalanches (Abele, 1974). Approximately equivalent terms in French are *chute de blocs* and *écroulement de falaise* (Labiouse *et al.*, 2001). Table I compares approximately equivalent terms in German, English, French, Norwegian and Italian languages based on common Swiss nomenclature.

In English terminology, the distinction between different types of rockfall remains ambiguous, despite some attempts at establishing arbitrary volume limits (e.g. Whalley, 1984). In practice and in the literature, small rock detachments are referred to as rockfall, while larger are usually described as rock slide. The term rock avalanche, loosely translated from the German ‘*sturzstrom*’ (rock slide stream, Heim, 1932), is usually reserved for very large rock failures (over 10^6 m^3) that disintegrate and become flow like and often highly mobile (Hungr *et al.*, 2001). However, flow like behaviour can also be observed in smaller rock detachments often, but not always with reduced mobility. The rockfall phenomenon can alternatively be classified based on the physical processes governing the event. Adopting Varnes’ definition literally, the fragments fall, bounce or roll largely independently of each other, experiencing strong mechanical interaction only with the slope surface but not with each other. These rockfall events, where the rocks interact only with the slope surface, can be called fragmental rockfall (Evans and Hungr, 1993). In reality, however, interaction between particles cannot always be ignored and there is a gradual transition from fragmental rockfall to granular flow, where semi coherent granular mass moves similar to a frictional fluid (cf. Table II). Following the suggestion of Nemcŏk *et al.* (1972) and Selby (1993), such events, the physics of which is governed by the interaction between the moving fragments, can be called ‘rock mass fall’. If the landslide is very large in magnitude and exhibits excessive mobility (see later), it should perhaps be called ‘rock avalanche’ (*Sturzstrom* by Heim, 1932).

Table I. Approximate comparison of practical rockfall terminology in five languages based on common Swiss nomenclature

German (Switzerland)	English	French	Norwegian	Italian	Involved particle size or volume
Steinschlag	Rockfall	Chute de pierres	Steinsprang	Caduta sassi	Mean projectile dimension up to 50 cm
Blockschlag	Rockfall	Chute de blocs	Steinsprang	Caduta massi	Projectiles larger than 50 cm, but smaller than 100 m^3
Felssturz	Rockfall, Rock slide,	Éboulement	Steinskred	Crollo in roccia	Rock volumes larger than 100 m^3 up to 10^6 m^3
Bergsturz, Sturzstrom	Rock avalanche	Écroulement	Fjellskred	Valanga di roccia	Rock volumes larger than 10^6 m^3

Table II. Proposal for an unambiguous definition of rockfall terminology

Rockfall term	1. Criteria: Transport mechanism	2. Criteria: Deposit characteristics[a]
Particle fall	Fragmental rockfall (individual particles do not interact with each other as much as with the substrate)	Fragment dimension up to 50 cm and total failed volume smaller than 100 m^3
Block fall/boulder fall (ERM, 1998)		Projectiles larger than 50 cm and total volume smaller than 100 m^3 or a limited number of discrete particles (maximum about 20)
Rock mass fall (Nemcǒk *et al*., 1972; Selby, 1993)	Dry granular flow (flow like movement, particles interact with each other and travel as deforming mass)	Volume ≥ 100 m^3 and a lobate deposit morphology
Rock avalanche	Granular flow with special mobilization phenomena (leading to extreme runout distances)	Volume ≥ 10 000 m^3 (in many cases more than several 100 000 m^3)

[a]The numerical deposit characteristics are not precise, but have been estimated based on experience.

Each of the two rockfall propagation processes is dominated by different physical processes. Fragmental rockfall must be analysed as the motion of a single rigid object, moving under gravity and interacting intermittently with the substrate. Rock mass fall, however, must be analysed dynamically as a granular flow remaining in a fairly continuous contact with the flow bed. Because the boundary between fragmental rockfall and rock mass fall is transitional, there will likely always be some uncer tainty in establishing a terminological distinction. No estab lished methodology presently exists for phenomena that are transitional between the two, as discussed later.

In this paper, the classification based on physical processes is used considering that, for purposes of modelling and predicting rockfall events, the physical processes governing the events are more important than the size of the event.

Propagation Mechanisms and their Analysis

Fragmental rockfall

Propagation of a rock fragment down a slope is a complex and strongly variable (random) process. Experimental results report the existence of four motion types   rolling, sliding, free fall, and impact. Pure sliding is almost always limited to initial acceleration of a fragment at the point of detachment and occurs only very rarely thereafter. The bulk of natural rockfall trajectories is achieved by free flight phases, separated by rebounds on the substrate. Pure rolling, where a fragment rotates, but remains in continuous contact with the ground, is rare due to the irregular shape of natural rock fragments and the roughness of the slope surface. Nevertheless, computer models often substitute rolling mode for movement consisting of very short bounces. Sliding is, in general, neglected.

An individual fragment falling from the slope follows the ballistic trajectory, except for intermittent contacts with the sub strate. Since routine analysis neglects air friction, the ballistic trajectory calculations are very simple and the behaviour of the fragment is completely determined by the interactions (impacts). An excellent means of visualizing the energy expenditure during propagation is provided by the energy line concept. The energy line is constructed on a profile of the trajectory of the fragment, by adding the 'translational kinetic energy head' $h_k = v^2/2g$ to the current elevation of the fragment which represents its potential energy (Figure 1). Rotational kinetic energy head, $h_r = R^2\omega^2/5g$ (for a sphere, R is the radius and ω the angular velocity) can be added to obtain the total energy line. While in air trajectory, the fragment rotates and loses no energy. Therefore, the energy line is horizontal. During an impact, there is an abrupt energy loss and re partition of energy between the translational and rotational mode. Thus, both the translational and total energy lines assume new eleva tions, which prevail during the subsequent episode of free flight. The energy changes during the impact depend on impact conditions. The energy line of a fragment moving in bouncing mode has the shape of a staircase, with the highest steps repre senting the most intensive impacts (Figure 1). If the rolling and sliding motion can be represented by the classical assumption of the Coulomb friction model with a constant friction coefficient, the energy line takes the form of a line sloping at

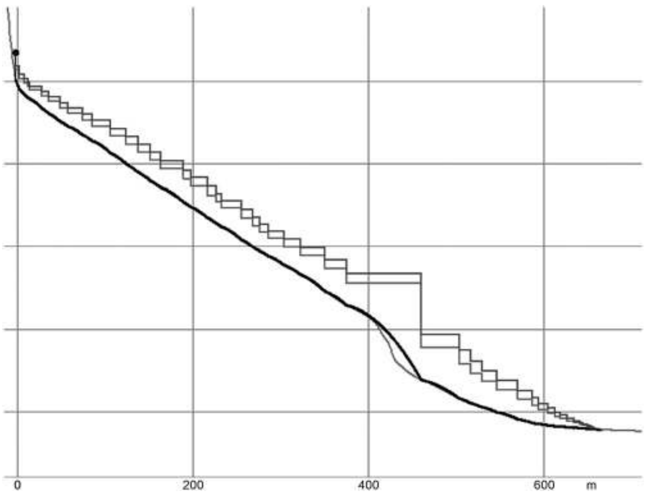

Figure 1. Example screen shot of a rockfall trajectory (thick black line) with the total energy line (translational and rotational; upper stepped line) and the translational energy line (lower stepped line).

a vertical angle equal to the tangent of the sliding (or rolling) friction coefficient.

The energy line representation clearly illustrates that the key element of a fragmental rockfall dynamic model is the rebound. The rebound is determined by the incident velocity vector magnitude and orientation, the shape (roughness) of the surface, the distribution of any deposits covering the substrate (including soil, boulders and vegetation) and the precise shape of the fragment and its position, orientation and angular velocity at the precise moment of contact. In the authors' opinion, no existing model approach is practically capable of describing all these conditions exactly and greater or smaller degrees of simplification are always required.

Mechanical properties of the slope surface strongly influence the rebound. Possible responses of the surface to the impact range from mainly elastic, recoverable strains for rock surfaces, to breakage of asperities on the surface or fragmentation of the particle, to the formation of large craters in weak soils involving substantial energy dissipation related to permanent frictional and plastic deformation within the soil. Complex mechanical models involving numerous parameters that may allow calcu lating these modes of energy dissipation exist in the literature (Bourrier and Hungr, 2011). These models are potentially also able to represent the significant influence of the kinematics of the rock before rebound. In particular, it is well known that flat incident angles and low incident velocity entail more energy conservation (Chau *et al.*, 2002; Bourrier *et al.*, 2008; Labiouse and Heidenreich, 2009). Also, the incident angle has signifi cant influence on transfers between the translational and rota tional energy components.

However, for real hillslope materials, complex models are very difficult to calibrate, due to the spatial variability of material properties at a given site. The choice is then usually made to use a simple mechanical model that requires a reduced number of variable parameters. Statistical calibration of these parameters permits embedding the complexity and the variability of the process (Bourrier *et al.*, 2009), while allowing an assessment in the field that is reasonably objective.

Mechanical properties of the rock projectile do not strongly influence the interaction, except if fragmentation occurs and is accounted for (Wang and Tonon, 2010). On the contrary, the size and the shape of the rock strongly influence the rebound as well as the energy transfers involved. For granular substrates such as talus slopes, the rebound is particularly strongly influenced by the ratio between the size and mass of the falling fragment and the average size and mass of particles forming the slope (Kirkby and Statham, 1975; Statham, 1979; Bourrier *et al.*, 2008), as well as the incident orientation of the fragment (Giani, 1992; Labiouse and Heidenreich, 2009) and the inertia of the rock fragment (Falcetta, 1985; Chau *et al.*, 1999; Heidenreich, 2004). The precise modelling of the rock size and shape is also not possible in practice. Fragment shapes are therefore approximated in analysis by idealized shapes, such as spheres or ellipsoids and rock size is randomized to reflect field difficulties in estimating it.

The accuracy of the simulation of fragmental rockfall events is also limited by the resolution of the slope profile or surface model, i.e. the digital terrain model. Despite the existence of very accurate surveying methods, such as LiDAR (light detec tion and ranging) scans, every modelled slope surface is a simplified picture of the real surface, usually consisting of joined linear segments or smooth curves. Thus, no impact model is a precise equivalent of an actual impact of a rock frag ment on a natural surface. The irregularities of both the surface and the projectile which cannot be simulated by the model must be embedded into the impact model using stochastic functions (cf. Dorren *et al.*, 2006). These can be introduced either as random variations of impact constants, or by a geo metrically based random roughness model, or by a combina tion of both. Additionally, objects on the slope such as trees, stumps or logs are generally accounted for in an implicit way by tuning slope roughness. Such a simplified point of view remains incomplete in particular for interactions with standing trees that have been proven to substantially change the frag ment propagation (e.g. Dorren *et al.*, 2005) and that are there fore explicitly modelled in some rockfall simulation codes (Volkwein *et al.*, 2011).

Rock mass fall

Landslide mobility is typically characterized by means of the 'Fahrboeschung', or travel angle, defined by Heim (1932) as the angle between the crown of the release area and the toe of the deposit, measured along the centreline of the path (see also Jaboyedoff and Labiouse, 2011). As noted by Heim, if a landslide is considered as a frictional flow phenomenon, the travel angle should be a rough approximation of the average friction angle acting on the base of the flow (more precisely, the measured angle should be based on the centres of gravity of the source mass and the deposit). However, well known empirical evidence indicates that rock mass movements exhibit greater mobility as their volume increases (Heim, 1932; Scheidegger, 1973; Abele, 1974). Many compilations of an inverse correlation between Fahrboeschung (or its tangent) and total rock volume have been published. A recent one, containing data from the last two decades not reported in earlier correlations, is shown in Figure 2. According to correlations such as shown in Figure 2, the friction angle prevailing on the base of rock mass fall is often as high as 38°, corresponding to the angle of internal friction of angular broken rock. However, often it is much less, due to certain mobilization phenomena that will not be described here (see, e.g. Hungr, 1990). Where such excessive mobility is observed, the term rock avalanche is appropriate, regardless of the volume of the event.

In recent years, dynamic models based on shallow water equations (also called Saint Venant equations), which are a set of hyperbolic partial differential equations that describe the flow below a pressure surface in a fluid, have appeared for simulation of flow like landslide motion (e.g. Savage and Hutter, 1989). Many results have indicated that granular rock fall can be satisfactorily simulated using flow resistance based on the Coulomb law of friction (e.g. Hungr *et al.*, 2005). The

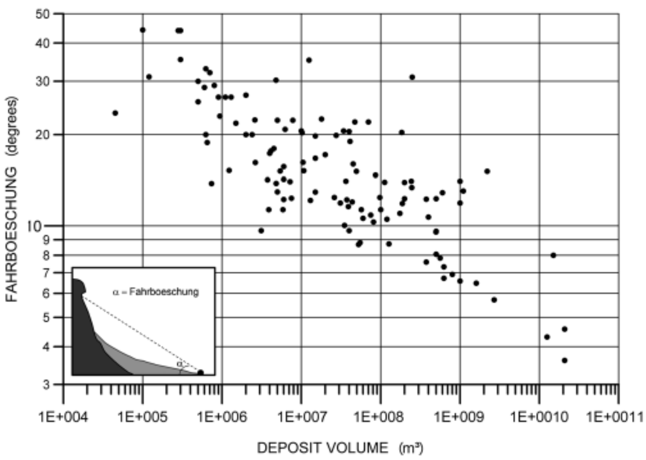

Figure 2. Compilation of Fahrboeschung volume data for rock ava lanches reported in the literature over the period 1990 2011 (C. Davidson, unpublished BSc thesis, University of British Columbia).

theory has been rigorously tested against controlled laboratory experiments using flow of dry sand on both smooth and rough substrates (e.g. Savage and Hutter, 1989; Hungr, 2008; Mancarella and Hungr, 2010). When applied to rock mass fall, these models can reasonably simulate the travel and deposition of masses of fragmented rock, moving as granular flows.

Many case studies show that large rock mass fall and rock avalanches can be modelled using such an approach. A recent example of an analysis was reported by Pirulli *et al.* (2011), who obtained an excellent estimate of the distribution of deposits from a two million m^3 rock avalanche in the Italian Alps, using a frictional model with a bulk basal friction angle of 31°. Another example is the back analysis of an 868 000 m^3 rock slide in the state of Washington by Strouth and Eberhardt (2009), where the flow of a mass of coarsely fragmented igneous rock was accurately simulated using a basal friction angle of 37° (Figure 3).

The frictional model, however, performs well only in cases where the fragmented rock mass flows over a relatively dry, firm substrate If the material in the path of the flow contains weak, saturated soil, the process of rapid undrained loading can spectacularly increase the mobility of the event and the resulting rock avalanche no longer behaves as a frictional flow. An example given by Hungr and Evans (2004) involves a 375 000 m^3 rock mass fall in marble and diabase, which fell on and eroded a colluvial apron of saturated silty sand. The entrained volume was another 360 000 m^3 and the resulting mass flowed for more than 1 km, to reach a Fahrboeschung of 13·8°. Dynamic back analysis of the event required the use of a velocity dependent frictional strength, whose frictional component was only 3°. Thus, runout prediction for rock mass fall requires detailed knowledge of the character of the material forming the path of the movement. Unfortunately, no system atic method exists of recognizing entrainable basal soils and

Figure 3. An aerial view of the source and part of the deposit of a small rock mass fall back analysed by Strouth and Eberhardt (2009).

the selection of flow resistance parameters must presently rely on subjective judgment and experience of the analyst.

The empirical phenomenon of greater mobility with increasing volume (cf. Scheidegger, 1973) can be plausibly explained using dynamic models. Firstly, the models predict strong longitudinal spreading of the grain mass during motion. Thus, the front of the deposit is projected further forward of the centre of mass and the Fahrboeschung becomes increasingly less than the angle between the centres of mass in larger slides. Secondly, larger rock mass falls naturally cover a larger area and therefore reach lower elevations on mountain slopes, where they have a greater chance of impacting saturated surficial material such as colluvium or alluvium, which are susceptible to liquefaction and entrainment (Hungr and Evans, 2004). Clearly, detailed knowledge of the sub strate forming the path of the landslide is necessary for successful model calibration and predictive use.

Transitional phenomena

Certain phenomena which are characteristic of the motion of fragmenting rock mass on steep slopes, complicate the practical use of granular flow models for rock mass fall. These phenomena occur especially with rock mass falls involving small volumes and could be considered as characterizing a transitional phenomena between rock mass fall and fragmental rockfall. Granular models assume that the rock block at the source instantly disintegrates into a granular mass. In reality, the initial movement following failure may be in the form of sliding or rota tion (toppling) of a block that remains initially more or less intact. Longitudinal or lateral spreading may only commence gradually, as the block disintegrates along the path. As a result, the spread ing predicted by granular flow type models is often excessive.

The extremely rapid frictional motion on rough, steep slopes, often projects the flowing mass into a ballistic trajectory. This temporally eliminates basal friction resistance and facilitates greater acceleration, but much of the gained kinetic energy may be consumed by impact deformation on landing.

The two processes mentioned earlier can be incorporated into numerical models. Figure 4 shows a typical example of a rock mass fall from a steep slope that exhibits transitional phenomena. It presents the ‘Happy Isles rock slide’, which took place in the Yosemite National Park in 1996. The event began as a sliding failure of approximately 30 000 m^3 of granitic rock (Wieczorek *et al.*, 2000). After sliding about 200 m over a steep rock face, the mass was projected into a ballistic trajectory and fell approximately 500 m, to land on a talus slope. Most of the rock debris then rapidly deposited and a spectacular air blast destroyed the forest within a distance of some 350 m from the impact site. Figure 4 shows an attempt to back analyse the event using the model DAN (Hungr, 1995) configured for a fric tional granular flow with a basal and internal friction coefficient of 38°. In order to achieve a reasonably faithful simulation of the event as described by Wieczorek *et al.* (2000), it was neces sary to prevent longitudinal and lateral spreading of the rock mass over the first 150 m of distance. The model was then modified to allow the flowing mass to detach from the path at a point when the centrifugal acceleration due to the vertical curva ture of the path exceeds gravity. The basal friction was turned off at this point and the mass was placed into a ballistic trajectory. Due to the high basal friction, the initial acceleration on the sliding ramp was only moderate. However, once launched into a trajectory, the modelled mass accelerated rapidly and was again projected forward by a glancing contact with a bench in the slope near 1600 m. Following this contact, the second ballis tic trajectory delivered the mass to the observed landing location on the talus apron. In order to simulate the limited subsequent

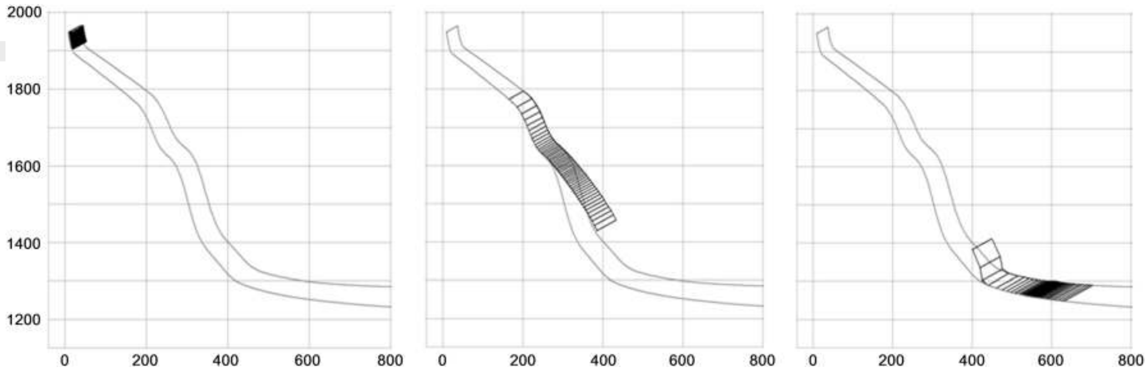

Figure 4. Dynamic analysis of the Happy Valley rock slide reported by Wieczorek (2000): (a) source block; (b) beginning of the second trajectory at 20 seconds; (c) shortly after landing, 30 seconds. Screen shots from the program DAN W. The grid lines are spaced 100 m vertically and 200 m horizontally. The highest elevation is 2000 m.

Figure 5. Saint Paul de Varces rock slide of 28 December 2008. Note boulder roll out and boulder size (a person is standing on the right side of the boulder) on the fields. Photographs: Sebastien Gominet (IRMa, Grenoble).

runout of the debris, it was necessary to specify an energy loss of at least 75% during the landing.

This simple model shows that typical transitional phenomena that occur on steep paths can be simulated, but not without substantial modifications to routine granular flow models. Much work remains to calibrate such tools to an extent required to obtain reliable predictions.

Another important process observed in small rock mass falls is the separation of large fragments from the granular flow. A rock mass failure results in fragmentation and a flowing movement of a poorly sorted mass of fragments over the slope surface. Initially, the entire mass slides and spreads over the initial part of the path. As the finer material flows down the slope surface and spreads out, the larger fragments begin to roll. They eventually separate from the flow, rolling ahead of the main body. At the end of the process, the finer material ends up spread over the proximal part of the slope at its angle of repose, while the larger boulders roll to and often beyond the toe of the slope. The process is easily observed on mine waste piles formed by end dumping of coarse rock waste, where the separated large fragments form a characteristic basal boulder concentration layer (e.g. Hungr *et al.*, 2001).

An excellent example of this process is the 1000 m^3 rock mass fall of 28 December 2008 at Saint Paul de Varces, Isere, France (Cemagref, 2011). The deposit of the event comprises two distinct facies (Figure 5): (1) a distributed sheet of finer grained granular mass, ranging from gravel to blocks less than 1 m in diameter, mixed with some amount of colluvium and deposited on slopes 32° to 38° just below the source area (in this area, the forest cover was completely destroyed and removed); (2) a group of larger boulders, 1 to 33 m^3 in volume, which rolled out more than 300 m ahead of the granular deposits, passed through a forested area and continued into open fields, reaching a 'rockfall shadow' angle of about 26° (compared to typical 27° as reported by Evans and Hungr, 1993). The granular deposit has been successfully simulated using the DAN model, with a basal friction angle of 35° and a small amount of substrate entrainment. The roll out of the large fragments was separately back analysed using the model Rockyfor3D, which simulates ballistic trajectories of fragmental rockfall (Dorren, 2012). Detailed results are described in Cemagref (2011). This example shows that it may be possible to model the two phases of an event of this type using separate models and this is the only way models can be used at present. Of course, such a procedure neglects the interaction of the two phases in the initial stages of the movement and the possible importance of this remains to be examined, once more experience with back analyses of such events is gained. The development of an integrated model for transitional events will require quantification of the process of decoupling of coarse and fine fragments, for which no algorithm presently exists.

Conclusions

The term rockfall comprises a spectrum of processes, including independent rolling and bouncing of individual fragments, flow of granular masses with or without substrate entrainment and transitional phenomena containing elements of both. Methods of analysis have been developed for the two end members of this spectrum, using rigid body ballistics and granular flow. Practically no development has yet been achieved to deal with the dynamic behaviour of the transitional processes, such as movement of granular masses in an air trajectory, incomplete disintegration of source blocks and decoupling of large rolling fragments from a flowing granular mass. Some simple means of dealing with these complications have been suggested in this article, but very considerable amount of fundamental method ological development still remains to be done. Calibration against full scale case histories is and will remain essential for all rockfall processes in the spectrum described in this article.

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