



Dynamic rock fragmentation: thresholds for long runout rock avalanches

E.T. Bowman
University of Sheffield
e.bowman@sheffield.ac.uk

ABSTRACT. The dynamic fragmentation of rock within rock avalanches is examined using the fragmentation concepts introduced by Grady and co-workers. The analyses use typical material values for weak chalk and limestone in order to determine theoretical strain rate thresholds for dynamic fragmentation and resulting fragment sizes. These are found to compare favourably with data obtained from field observations of long runout rock avalanches and chalk cliff collapses in spite of the simplicity of the approach used. The results provide insight as to the energy requirements to develop long runout behaviour and hence may help to explain the observed similarities between large rock avalanches and much smaller scale chalk cliff collapses as seen in Europe.

KEYWORDS. Flow; Dynamic fragmentation; Rock avalanche; Strain rate.

INTRODUCTION

Large rock avalanches present a serious mountain hazard, however, there is a still considerable debate over the mechanisms of their collapse and transport. Due to the size and temporal unpredictability of rock avalanches there is currently no possibility to militate against their effects other than by infrastructure planning. As a result, the extremely long travel distances and high velocities that may be attained is of great concern to hazard modellers and engineers. Understanding the mechanical processes that govern rock avalanche behaviour may lead to better predictive modelling. This paper discusses dynamic rock fragmentation which is thought to play a major role in the high transport mobility of rock avalanches.

Large terrestrial rock avalanches generally comprise volumes of order 0.01 - 500 million m³, covering areas from 1 - 500 km², and initial potential energies between 10¹⁴ – 10¹⁸ J [1]. They also have a fall height to length ratio (the tangent of which is known as the “*farboschung* angle”) that is a reducing function of volume [2]. A method to characterize the size dependence of rock avalanche mobility is the “spreading efficiency” defined as the ratio of runout length to the cube root of volume ($L/V^{1/3}$), which has been show to vary from 6-10 [3]. In comparison, simple small scale experiments in which dry sand or rock blocks have been released to flow down a slope, generally produce spreading efficiencies of 1.5-3 [3]. The value is much lower than found for field scale rock avalanches, implying a much lower mobility for small experimental flows. Equally significantly, this value has not been found to increase with volume which suggests that potential energy is not so important for the emplacement of these small flows. One promising hypothesis for the extraordinary mobility of large rock avalanches involves the process of dynamic fragmentation of rock and how this may lead to a reduced frictional resistance within the mass [4, 5].



FIELD OBSERVATIONS

Field observations may help us to understand what additional processes are at work during rock avalanche propagation and arrest, beyond sliding, rolling, shearing and frictional dissipation, as observed for small scale experiments. Common observations of large rock avalanches are that: they attain high velocities (e.g. 75 m/s average was determined for the Huascarán rock avalanche in Peru, 1970, with some boulders flung out at up to 280 m/s [6]); the deposits are very thin (e.g. averaging 5 m thick at Elm, Switzerland [7] in 1881; Fig. 1, left); there is a lack of sorting and mixing of debris, with geological layers being preserved intact; and, there is an extremely high degree of fragmentation of the rock within the deposit typically below a surface shell or “carapace” of intact blocks [5]. Recently, the spreading efficiency of rock avalanches has been found to correlate positively with the degree of fragmentation of the deposit [4] – i.e. the change in grain size distribution from the commencement to arrest – indicating that high mobility is linked to dynamic rock fracture.



Figure 1: Left: Mt Haast rock avalanche (also known as Mt Dixon rock avalanche) that occurred on 21st January 2013 in the southern Alps of New Zealand (details in Hancox & Thomson, 2013 [8]). Right: Chalk cliffs of south Kent. Collapse deposits are generally rapidly eroded by wave action but leave characteristic rock shelf extensions. Photos: Author.

The large size of high mobility rock avalanches is, in itself, interesting to note. Below 0.01 million m³, and potential energy of 10¹⁴ J, rock falls, characterised by bouncing, rolling and breaking blocks, are common but long runout behaviour is almost unknown. The exception to this appears to be the long runout collapses of chalk cliffs that occur in parts of Europe (Fig. 1, right). Such collapses can behave very much like large rock avalanches, displaying low to high spreading efficiency ($L/V^{1/3}$ from 0.5 – 7) [9] at much smaller volumes (10³ m³ - 10⁶ m³) and with much lower initial potential energy (up to 10¹⁰ J). As discussed by Bowman and Take (2014) [10], the reasons for the similarities with rock avalanches are likely to be due to the low strength of the chalk in comparison with more typical rocks, with weak chalk producing the greatest spreading efficiency.

These observations point to two processes: a high degree of particle fragmentation via comminution, and a predominance of collisional stress transfer between closely spaced (or even touching) fractured particles. This paper examines how the dynamic fragmentation of rock during avalanche propagation may lead to enhanced mobility. The paper focuses on comparisons between events involving two different rock types – i.e. limestone, which is a common source rock in long



runout avalanches, and weak chalk, which is found to produce long runout behaviour in chalk cliff collapses. In doing so we attempt to shed light on the role of dynamic fragmentation on generating high mobility via high speed fragment dispersal.

DYNAMIC FRAGMENTATION

As discussed by Zhang (2002) [11], the empirically noted close relationship between tensile strength σ and fracture toughness K_{IC} for rock appears to be related to the general failure mode of rock. During compressive loading, rock fails by tensile splitting, with little shearing of the surfaces – such that the ultimate compressive strength σ_c is found to be approximately 8-15 times σ [12]. Indeed failure, whether in shear, compression or tension, tends to occur by the growth of tensile microcracks, supporting the use of fracture mechanics to examine failure. This view is further supported by examining the failure surfaces of fracture toughness and tensile strength test specimens, which are similar – with the samples of static tests showing the extension of a single flaw or the coalescence of a few microcracks, and those of dynamic tests revealing branching macrocracks and additional damage beyond the main surface [11].

It is generally accepted that rocks exhibit strain rate dependent strength, with a very weak to weak dependence at low strain rates and a much stronger dependence once a threshold strain rate is exceeded [13-15] – a behavioural regime we refer to here as “dynamic”. For rocks with larger grains, larger flaws, or a greater degree of heterogeneity, the threshold strain rate tends to be lower [16]. Over this threshold, dynamic fragmentation produces a more damaged material, and more, smaller, fragments with increasing strain rate. The fragments produced possess increased kinetic energy with strain rate, creating inefficiencies in industrial processing [17] and, it is hypothesized here, resulting in greater mobility of rock avalanches.

ANALYSIS

Tab. 1 lists properties typical of the two rock types that are used in the following analyses.

In this analysis, we follow the mechanism of dynamic fragmentation proposed by Grady [18] to compare theoretical fragment sizes produced under rock avalanche conditions with observations made in the field. In Grady and Kipp’s analyses [16, 19] they show that the initiation of dynamic fragmentation is dependent on the inherent flaw size as with static breakage. They treat the problem in two ways – first by examining material failure through an inherent flaw concept, and second through the use of fracture mechanics.

Property	Weak chalk	Limestone
Tensile strength σ (MN/m ²)	0.3	8
Quasistatic fracture toughness K_{IC} (MN/m ^{3/2})	0.045	1.1
Density ρ (kg/m ³)	1610	2700
Speed of sound c (m/s)	2300	5000

Table 1: Properties used in analysis

In quasistatic breakage of a brittle material, the largest or most critical flaw is considered to be responsible for fracture [20]. Using the Griffith / Irwin failure criterion, the theoretical failure stress may be determined by assuming tensile loading of an isolated flaw that is (for example) penny-shaped. Conversely, if the fracture toughness K_{IC} and tensile strength σ of the material are known, a theoretical maximum flaw size r_0 amongst a distribution of flaw sizes r may be determined [20]:

$$r_0 = \frac{\pi K_{IC}^2}{4\sigma^2} \tag{1}$$

From Eq. 1 and Tab. 1, for chalk, r_0 is found to be 16.6mm and for limestone, r_0 is found to be 14.8mm. These values are rather similar, despite the large differences in strength of the materials, possibly reflecting their similar geological origins.



At higher loading rates, it is not possible for the critical (largest) flaw to grow fast enough to relieve the applied stress in the time provided. As a result, other, smaller, flaws must come into play, leading to multiple fractures and a material that is more pervasively damaged or fragmented [16]. Under constant strain rate loading and an assumed Weibull distribution of flaws, and by assuming that all activated cracks / flaws propagate at constant velocity, Grady and Kipp (1987) determined a relationship for the peak failure stress dependent on several properties of the material (elastic modulus, Weibull parameters, and crack propagation velocity), and of strain rate as a function of the Weibull modulus. Their second treatment addresses the crack growth process explicitly for a single isolated crack under dynamic loading. Here, linear elastic fracture mechanics is applied to a (for example) penny-shaped crack. An expression for the stress to initiate fracture on an isolated crack / flaw under dynamically applied stress is obtained that is a function of several material constants (pseudostatic K_{IC} , elastic modulus, and speed of sound in the material), and of the cube root of the applied strain rate. To reconcile the two approaches, the Weibull parameter m , must be equal to 6, which is a good fit to many rock types, albeit not all [16, 21]. The theoretical dynamic strength for a penny-shaped crack undergoing constant strain rate loading [19] is therefore:

$$\sigma = \sqrt[3]{\frac{9\pi}{16} \rho c K_{IC}^2 \left(\frac{d\varepsilon}{dt}\right)^{1/3}} \quad (2)$$

Where ρ is the density and c is the speed of sound in the material. Fig. 2 shows this relationship for the weak chalk and limestone, respectively, compared with the static strength (assumed to be negligibly rate dependent here) of both. It may be expected that the static strength will be valid below the crossover points, upon which the behaviour will converge to the rate dependent response with increasing strength with strain rate.

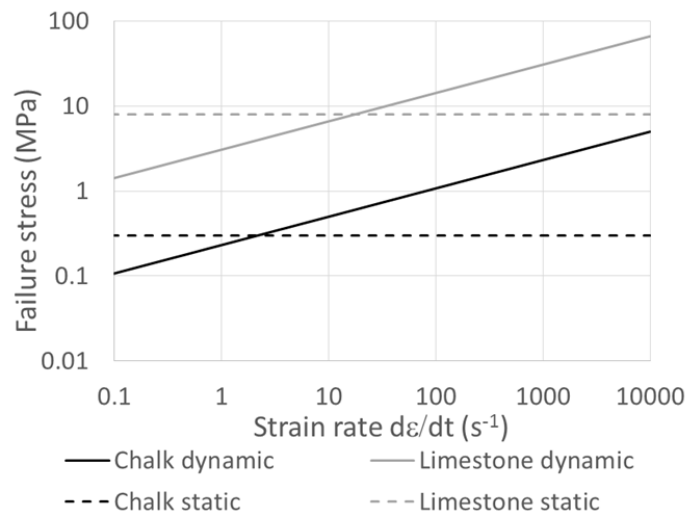


Figure 2: Predicted theoretical dynamic strength against strain rate compared with static strength for typical weak chalk and limestone.

Further analyses are needed to indicate at what strain rate the dynamic regime commences and to give information as to the size of the fragments produced in the dynamic regime. Once again invoking fracture mechanics principles, Grady and Kipp (1979) [19] determine a minimum strain rate $(d\varepsilon/dt)_{\min}$ at which pseudostatic fracture gives way to dynamic fragmentation, as follows:

$$\dot{\varepsilon}_{\min} = \left(\frac{d\varepsilon}{dt}\right)_{\min} = \frac{K_{IC}}{\rho c r_0^{3/2}} \quad (3)$$

Fig. 3 shows this relationship plotted using typical data for weak chalk and limestone, respectively. The intersections of the predicted maximum flaw sizes r_0 obtained from the static analyses (Eq. 1) are also plotted, giving a minimum strain rate at which dynamic fragmentation is predicted to occur for the two materials. Although r_0 is very similar for the two rocks types, the resultant $(d\varepsilon/dt)_{\min}$ is quite different; $5.5s^{-1}$ for chalk and $45s^{-1}$ – i.e. an order of magnitude increase from chalk to limestone.

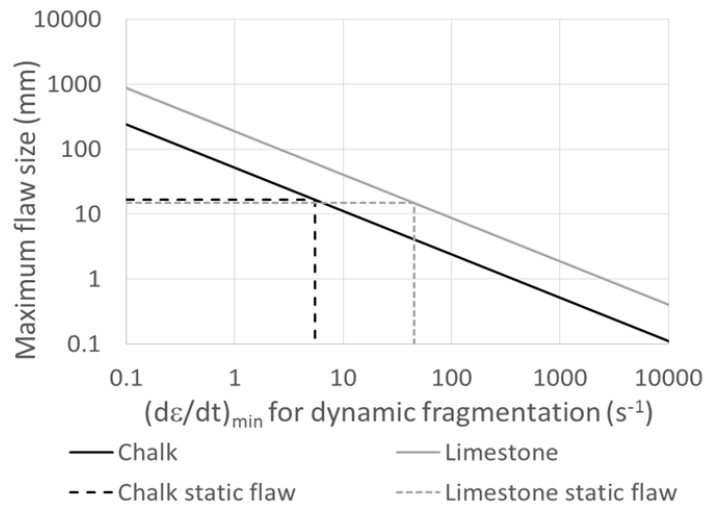


Figure 3: Theoretical relationship between maximum flaw size r_0 and resultant minimum strain rate for dynamic fragmentation, compared with actual flaw size predicted from the pseudostatic condition for a typical weak chalk and limestone.

Finally, in order to determine fragment sizes produced during a dynamic event, following Grady (1982) [18], Grady and Kipp (1987) [16] adopt an energy approach to the dynamic loading regime in which a balance between local kinetic energy and fracture energy is made. That is, once this regime is reached, the fragment size no longer depends on the initial size of the flaws but rather upon the kinematic conditions imposed. The numbers of fragments are found to depend on the strain rate applied, with smaller and greater number of fragments being produced at higher strain rates. The resulting relationship for fragment size d is:

$$d = \left(\frac{\sqrt{20}K_{IC}}{\rho c d\dot{\epsilon}/dt} \right)^{2/3} \quad (4)$$

Eq. 4 and its derivatives have been found to reasonably approximate the characteristic size of fragments from different experimental arrangements on different brittle and quasi-brittle materials [22, 23]. Fig. 4 plots the relationship predicted by Eq. 4 for weak chalk and limestone, respectively.

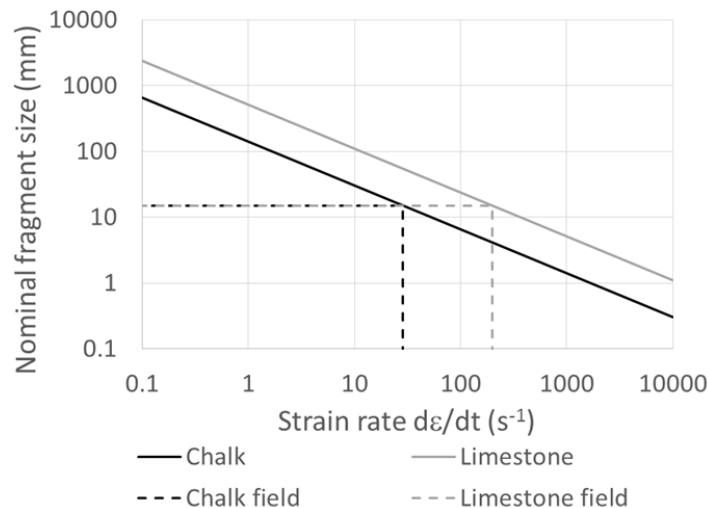


Figure 4: Theoretical relationship between the nominal fragment size produced and the strain rate during a constant rate of strain dynamic event, compared with mean field values typical for long runout rock avalanches in limestone and cliff collapses in weak chalk.



In comparison, typical mean fragment sizes found in chalk cliff collapse and rock avalanche deposits [7] are shown, giving an approximate value of strain rate that might be expected to be required to generate such a size of fragment. For weak chalk, the strain rate is determined as around 30s^{-1} , while for limestone the strain rate is around 200s^{-1} .

DISCUSSION

A simple approximation of how dynamic strain rates equate to velocity may be determined as:

$$v = D \frac{d\varepsilon}{dt} \quad (5)$$

Where v is differential velocity (impulsive, impact or shear) and D is the initial particle size which may be taken as the typical fracture spacing of the intact rock. Typical values are 0.5m for chalk and 1m for limestone. For the analysis of threshold strain to attain dynamic fragmentation, based on Fig. 3, the velocities are therefore 2.8m/s and 45m/s for the chalk and limestone, respectively. Based on a free-fall condition, the chalk would attain such a velocity at 0.4m – in other words, a very small movement in the field is all that is needed to enter the dynamic regime. For the limestone, a velocity of 45m/s is a lower bound of the mean frontal velocities determined for many rock avalanche events and it may not be a coincidence that few rock avalanches with mean velocities low that this value have been recorded. That is, this velocity, as translated to strain rate within the avalanches may signal a minimum to reach dynamic behaviour in typical materials.

For the analysis of actual strain rates achieved in typical events that produce the fragment sizes seen (Fig. 4), resultant velocities are 15m/s for the chalk and 200m/s for the limestone. While there are few eyewitness accounts in which quantitative assessments of chalk cliff collapses are available, the value derived for chalk is equivalent to that attained by a free-fall velocity over 11m, which would be a minimum height of fall required. Considering that the cliffs in question tend to be between 20 and 90m and near vertical [10], this accords well with the field condition. For limestone, a 200m/s differential velocity is comparable to mean travel velocities of 45-90 m/s and the observations of boulders being flung out of the mass at much higher speeds – suggestive of internal differential velocities that are higher than the mean [6].

It has further been noted that the fragments that result from dynamic fragmentation possess kinetic energy that is “left over” from the fragmentation process [18]. Such behaviour has been noted also experimentally [17], although there currently does not appear to be any explicit theoretical treatment of how exactly energy is partitioned post-fracture, rather the focus has been on the size and numbers of fragments produced. Following this, the analysis in this paper has determined the threshold strain rates for dynamic fragmentation of chalk and limestone materials and noted that both thresholds are likely to be exceeded for typical field geometries involving long runout.

CONCLUSIONS

While the treatment here of dynamic rock fragmentation using the concepts introduced by Grady [18-19] is highly simplified, applying this approach to rock avalanche behaviour appears to capture some essential mechanisms involved in their propagation. These include, most notably, the strain rate – strength dependency of fragmentation and the dominant fragment sizes as found in field deposits. The results using typical material properties of weak chalk and limestone compare favourably with field observations and help to shed light on why it may be that chalk cliff collapses in weak chalk behave similarly to large scale long runout rock avalanches (and conversely, why stronger chinks would fail to produce the same behaviour). A number of assumptions have been made in the analyses including the conversion of potential / strain energy through breakage at constant strain rate and representing the whole deposit of highly fragmented rock by a single fragment size. Clearly this is a highly idealized representation of reality and further work is needed to develop the analysis in terms of fragmentation behaviour and to show how fragmentation explicitly can lead to long runout. Recent work on fragmentation in ceramics [24], which are closely analogous to rocks, has validated Grady’s energy approach in the limit to reproducing the behaviour of dynamically fragmenting ceramics under complex scenarios, albeit with numerical modifications. Such work provides encouragement to the further development of the approach to examining rock avalanche dynamics.



REFERENCES

- [1] Dade, W.B., Huppert, H.E. Long-runout rockfalls. *Geology*, 26 (1998) 803-6.
- [2] Scheidegger, A.E., On the prediction of reach and velocity of catastrophic landslides, *Rock Mechanics*, 5 (1973) 231-6.
- [3] Davies, T.R., McSaveney, M.J., Runout of dry granular avalanches, *Canadian Geotechnical Journal*, 36 (1999) 313-20.
- [4] Bowman, E.T., Take, W.A., Rait, K.L., Hann, C., Physical models of rock avalanche spreading behaviour with dynamic fragmentation, *Canadian Geotechnical Journal*, 49 (2012) 460-76.
- [5] Davies, T.R.H., McSaveney, M.J., The role of dynamic rock fragmentation in reducing frictional resistance to large landslides, *Engineering Geology*, 109 (2009) 67-79.
- [6] Plafker, G., Ericksen, G.E., Nevados Huascarán avalanches, Peru. In: *Rockslides and Avalanches 1. Natural Phenomena*, Voight, B. Ed., Elsevier, New York, 1 (1978) 277-314.
- [7] Hsu, K.J., Heim, A., Observations on landslides and relevance to modern interpretations. In: *Rockslides and Avalanches 1. Natural Phenomena*, Voight, B. Ed., Elsevier, New York, 1 (1978) 71-93.
- [8] Hancox, G.T., Thomson, R., The January 2013 Mt Haast rock avalanches and Ball Ridge rock fall in Aoraki / Mt Cook National Park, New Zealand. In: *Report 2013/33, GNS Science* (2013).
- [9] Hutchinson, J.N., Chalk flows from the coastal cliffs of northwest Europe. In: *Catastrophic landslides: effects, occurrence, and mechanisms* Evans, S.G., DeGraff, J.V. Eds., Geological Society of America, Boulder, Colorado, 15 (2002) 257-302.
- [10] Bowman, E.T., Take, W.A., The runout of chalk cliff collapses in England and France—case studies and physical model experiments. *Landslides*, (2014) Online First.
- [11] Zhang, Z.X., An empirical relation between mode I fracture toughness and the tensile strength of rock. *Rock Mechanics and Mining Sciences*, 39 (2002) 401-406.
- [12] Jaeger, J.C., Cook, N.G.W., Zimmerman, R., *Fundamentals of Rock Mechanics* 4th ed, Wiley-Blackwell, (2007).
- [13] Brace, W.F., Jones, A.H., Comparison of uniaxial deformation shock and static loading of three rocks. *Journal of Geophysical Research*, 76 (1971) 4913-4921.
- [14] Green, S.J., Perkins, R.D., Uniaxial compression tests at varying strain rates on three geologic materials. In: *10th U.S. Symposium on Rock Mechanics (USRMS) Austin, Texas, (1968)* 35-54.
- [15] Yu, S.-s., Lu, Y.-b., Cai, Y., The strain-rate effect of engineering materials and its unified model. *Latin American Journal of Solids and Structures*, 10 (2013) 833-44.
- [16] Grady, D.E., Kipp, M.E., Dynamic fragmentation of rock. In: *Fracture Mechanics of Rock*, Atkinson, B.K. Ed., Academic Press, San Diego, California, (1987) 429-475.
- [17] Zhang, Z.X., Kou, S.Q., Jiang, L.G., Lindqvist, P.-A., Effects of loading rate on rock fracture: fracture characteristics and energy partitioning, *International Journal of Rock Mechanics and Mining Sciences*, 37 (2000) 745-762.
- [18] Grady, D.E., Local inertial effects in dynamic fragmentation, *Journal of Applied Physics*, 53 (1982) 322-5.
- [19] Grady, D.E., Kipp, M.E., The micromechanics of impact fracture of rock, *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts*, 16 (1979) 293-302.
- [20] Shockey, D.A., Curran, D.R., Seaman, L., Rosenberg, J.T., Petersen, C.F., Fragmentation of rock under dynamic loads, *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts*, 11 (1974) 303-317.
- [21] Grady, D.E., Lipkin, J., Criteria for impulsive rock fracture, *Geophysical Research Letters*, 7 (1980) 255-258.
- [22] Grady, D.E., Olsen, M.L., A statistics and energy based theory of dynamic fragmentation, *International Journal of Impact Engineering*, 29 (2003) 293-306.
- [23] Grady, D.E., Kipp, M.E., Mechanisms of dynamic fragmentation: factors governing fragment size, *Mechanics of Materials*, 4 (1985) 311-20.
- [24] Levy, S., Molinari, J.F., Dynamic fragmentation of ceramics, signature of defects and scaling of fragment sizes, *Journal of the Mechanics and Physics of Solids*, 58 (2010) 12-26.