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DYNAMIC FRAGMENTATION IN LANDSLIDES: APPLICATION TO NATURAL DAM STABILITY

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INTRODUCTION

The most common and widespread geomorphic effect of landslides is to block a drainage system forming a landslide dam. The stability of landslide dams is of the utmost importance; if the dam fails, it releases the impounded water to form a potentially destructive dambreak flood, and it also releases the debris of the dam and any accumulated reservoir sediment to the river downstream, causing severe aggradation and progressive channel instability. Landslide dam stability depends to a large extent on the material comprising the dam. This in turn depends on the nature of the source material and on the processes that modify it during the travel of the landslide. The fragmentation that occurs in rock avalanche motion results in a distinctive grading in the interior of a deposit, while the surface and upper several metres of the deposit comprise much less intensely fragmented clasts. By contrast, landslide dams formed by blockslides usually comprise relatively intact material; the fragmentation that influences the motion of the block is confined to a thin basal layer. Such dams are less likely to fail than those formed by rock avalanches.

In recent papers (DAVIES & MCSAVENEY, 2002; MCSAVENEY & DAVIES, 2003) we have proposed that the extraordinarily long travel distance of large rock avalanches results from internal dispersive stresses caused by dynamic rock fragmentation during runout. We have also (DAVIES & MCSAVENEY, 2003) suggested that fragmentation at the base of large low-angle blockslides explains their extraordinarily long travel. A clear picture of the mechanical processes of material modification that occurs in rock avalanche and blockslide motion is thus of critical importance for understanding the extent and assessing the stability of deposits which block rivers, and this paper reports and substantiates such a picture. We then consider the implications of the presence of fragmented rock material for the stability of landslide dams.

STRESSES WITHIN A FRAGMENTING ROCK AVALANCHE

MAGNITUDE OF STRESSES

DAVIES & MCSAVENEY (2002) used a one-dimensional numerical model (HUNGR, 1995) to show that the time- and depth-averaged internal longitudinal dispersive stress needed to simulate the runout of two rock avalanches in New Zealand is of the order of five times the average geostatic stress of the deposit; in the case of the 55 x 10^6 m^3 Falling mountain event (DAVIES & MCSAVENEY, 2002) this is about 2.5 MPa. If the stress generated by a single fragmenting grain were 2.5 MPa, then every grain in the avalanche would need to fragment simultaneously to develop the required stress, and the isotropic dispersive stress at all points within the translating debris mass would exceed the geostatic stress by about a factor of five. This would cause the whole mass to explode in every direction at about 5g (J.N. Hutchinson, Imperial College, London, pers comm 2003). There is no field evidence for such behaviour. It therefore cannot be the case that all (or even the majority) of grains are fragmenting simultaneously, so the local stress due to a grain fragmenting must be much greater than the spatially averaged dispersive stress.

With a small proportion of grains fragmenting at any time, the upward vertical component of the dispersion caused by any particular fragmentation event will be fully reversed by gravity before the next event occurs in the vicinity. Hence, no net work is accomplished in the vertical direction by this mechanism. Hence local, intermittent high isotropic dispersive forces do not necessarily cause general upward motion of a granular mass. By contrast, instantaneous longitudinal dispersions are not reversed by gravity, but persist until the next fragmentation event in the vicinity. The absence of substantial and general upward explosion of rock avalanches is thus not evidence for the absence of locally high isotropic dispersive stresses during runout.

An experimental indication of the magnitude of the dispersive stress generated by rock failure comes from WAWERSIK & FAIRHURST (1970). They carried out inelastic unconfined compression tests on a variety of rock types at low shear rates (10-5 per s, and found two modes of failure; one (Class I) in which failure envelopes showed decreasing stress with increasing strain, and one (Class II) in which axial strain briefly reversed against the applied compressive stress (Figure 1). In the latter case, if the failure stress path follows the envelope during rapid stress application, the dispersive stress generated by failure exceeds the applied compressive stress. Such Class II behaviour, once initiated, requires no further input of energy to complete the fragmentation, and the failure would proceed rapidly and explosively; this is well known to be the case in dynamic rock fragmentation (WAWERSIK & BRACE, 1971; MCSAVENEY & DAVIES, 2003). WAWERSIK

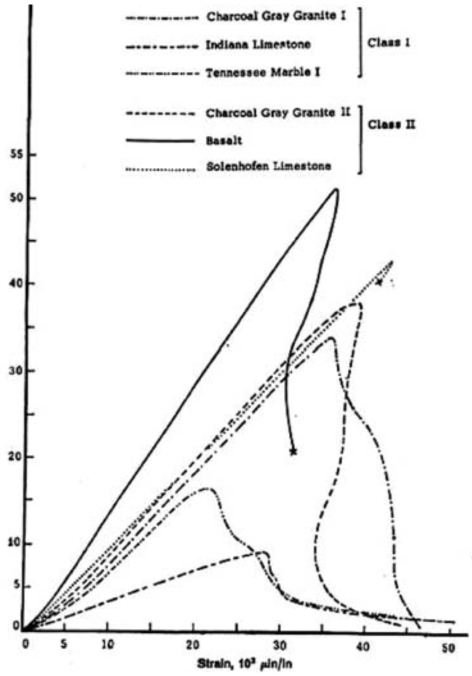

Figure 1 - Stress-strain curves from W*AWERSIK* & F*AIRHURST* *(1970)*

& FAIRHURST (1970) comment that Class II behaviour might occur more widely at higher strain rates. The fact that Class I behaviour did not result in a reversal of strain at failure suggests the conservative conclusion that the local dispersive stress generated by a fragmenting rock particle is approximately equal to the unconfined compressive strength of the particle.

In the Falling Mountain example, the local fragmentation-induced dispersive stress is of the order of 0.5 GPa (DAVIES & MCSAVENEY, 2003); to obtain a spatially averaged stress of 2.5 MPa then requires that one grain in about 200 is fragmenting at any instant.

DIRECTION OF STRESSES

Fragmentation of a rock particle in the shear field of a large rock avalanche will deliver non-isotropic forces to its surrounding grains if it breaks into only a few pieces. However, if the stress generated by any individual grain fragmentation is randomly oriented, then the number of fragmentation events occurring in any sizable aggregate of grains is large enough that the integrated effect of even non-isotropic individual stresses will be that of a uniformly isotropic stress. In addition, only isotropic stresses - not shear stresses - can be transmitted in materials stressed above their Hugoniot elastic limits. The ubiquitous presence of finely comminuted rock shows that rock-avalanche material has been repeatedly stressed beyond its elastic limit.

GRAIN-SIZE DISTRIBUTION OF ROCK-AVALANCHE MATERIAL

Grain-size distributions of rock avalanches and several fault gouges from a variety of published and unpublished data from New Zealand and elsewhere (Figure 2; S. Dunning, Durham University, U.K., pers. comm.) all have a fractal dimension close to 2.58, a value found by SAMMIS *et alii* (1987) to correspond to a three-dimensional geometry that equalises and minimises the probability of fracture of all particles. Thus all grains present in a rock avalanche are similarly likely to fragment at any given time.

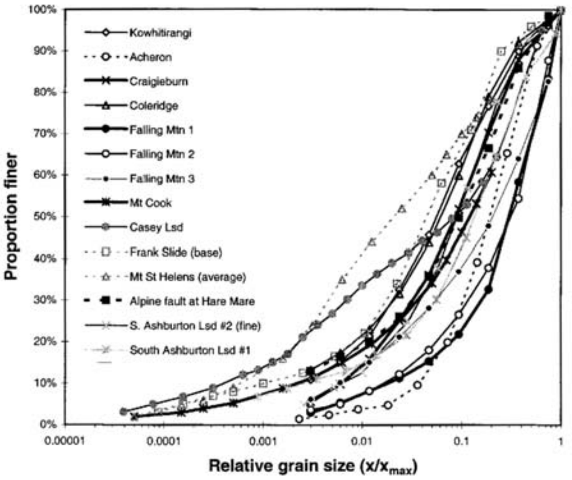

Figure 2 - Rock avalanche grain-size distributions (with gouge from Alpine fault, NZ also shown)

FRAGMENTATION OCCURS THROUGHOUT THE RUNOUT

It is fundamental to our explanation that fragmentation occurs throughout the runout, and we have a number of supporting facts:

1) shattered undisaggregated clasts are often found close to the distal margin at depth within rock avalanche deposits. Such clasts could not have been shattered at the onset of motion and retained their aggregation for the duration of the avalanche.
2) the deposit of the Vaiont landslide (ERISMANN & ABELE, 1999), which travelled only a relatively short distance before halting, is not fragmented.
3) the Köfels landslide deposit (ERISMANN & ABELE, 1999) is not completely fragmented; in particular, one component of the mass that was halted by an obstruction is fairly intact.

Dispersive stresses due to fragmentation are therefore present throughout the fall and runout of a rock avalanche.

CONCEPTUAL MODEL OF FRAGMENTATION

Figure 3 illustrates our concept of fragmentation in a rock avalanche. The fragmentation of individual grains is represented by stars of various sizes; particles of all sizes are fragmenting at any one time, each generating a local isotropic dispersive pressure, the integrated longitudinal component of which causes increased spreading during translation. The local dispersive stress generated with each fragmentation is assumed to be constant at about 0.5 GPa. The grain-size distribution (and therefore the fractal dimension) does not vary with depth below the carapace (S. Dunning, Durham University, U.K., pers. comm.), suggesting that the spatial probability of occurrence of fragmentation events is the same at all levels below the carapace.

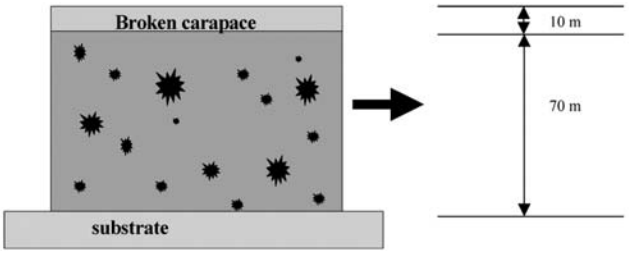

Figure 3 - Diagram of fragmentation in rock avalanche; dimensions refer to Falling Mountain situation

APPLICATION TO BLOCKSLIDES

A remarkable prehistoric landslide deposit at Waikaremoana, North Island, New Zealand is interpreted as a low-angle rapid blockslide (Beetham *et alii*, 2002), in which a 1.2 km^3 intact block of sandstone moved about 2 km on a sandstone surface sloping at about 5° to the horizontal at a speed of up to 30-50 m/s (Figure 4). The long, accelerating travel on a very low-angle surface requires that there was very low frictional resistance to motion of the block on the sandstone substrate. We now suggest that this low friction was due to rock fragmentation occurred at the sliding interface, given the inevitable initial rugosity expected of any failure surface within intact rock.

A 0.3 m thick layer of finely-ground rock at the base of the displaced block recently has been proven by drilling (R. Beetham, GNS, Lower Hutt, N.Z. pers. comm.), and is interpreted as the fragmented material. The vertical dispersive pressure generated by fragmentation of individual clasts, if applied directly to the underside of the detached intact block, provides sufficient vertical force to support most of the weight of the block during motion (Figure 5). This reduces the normal stress between the block and its substrate, and hence the frictional resistance to motion; a fragmenting rock at the substrate-block interface cannot transmit any shear force because it is stressed above its Hugoniot elastic limit. We now have experimental evidence for this effect. Analysis of the stresses involved (Davies *et alii*, in prep.) shows that fragmentation of one particle in about 35 is required to explain the acceleration of the block to the velocity required to match that inferred by Beetham *et alii* (2002).

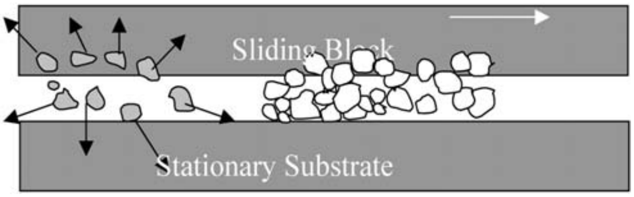

Figure 5 - Fragmenting grain supports weight of block reducing direct stress on adjacent shearing non-fragmenting debris

APPLICATION TO LANDSLIDE DAMS

Fragmented rock avalanche debris dominates the material properties of landslide dams, and their ability to resist failure due to overtopping, slope failure or piping. A large rock avalanche deposit comprises an unstructured fragmented mass of all grain sizes, apart from the top several metres, which has a much higher proportion of larger clasts. The surface layer of large clasts often gives rock avalanche deposits the appearance of being comprised completely of angular boulders (Figure 6). However, the material beneath the surface carapace is finely fragmented (Figure 7), and matrix-rather than clast-supported, and is very erodible if the carapace is penetrated by water flow. The finer subsurface material, however, is likely to be of low permeability when saturated due to its wide grading and the consequent very small average void size. It is therefore likely that seepage rates will be low following emplacement of the dam, and that slumping of the downstream dam face due to daylighting of the phreatic surface is likely to require a long time to occur, and is therefore relatively unlikely prior to overtopping. This was the case with the Poerua landslide dam in Westland, New Zealand (Hancox *et alii*, 1999). Similarly, piping failure has a lower likelihood than overtopping, because the widely-graded material of the

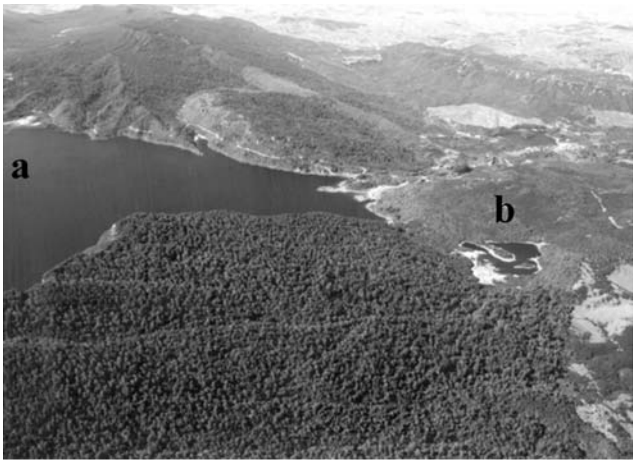

Figure 4 - Waikaremoana blockslide (b) and landslide-dammed Lake Waikaremoana (a)

Figure 6 - Green River rock avalanche deposit, British Columbia, Canada showing uniformly large surface clasts

Figure 7 - Section through Green River rock avalanche deposit, showing finely crushed material below upper 10 m

dam acts as an effective filter, and even when seepage has developed it is unlikely that void spaces will be sufficiently large to allow particle migration.

Not all overtopping events cause failure; the Poerua dam initially overtopped about 2 days after emplacement, but did not fail until 5 days later in a higher flow event. This could be due to saturation of the downstream slope by seepage from the overflow water, or to translation of the phreatic surface to the downstream face during the interval. Alternatively, the failure could have been caused by the greater and more erosive flow in the failure event. Some landslide dams do not fail. Recent attempts to identify the factors that determine whether or not a landslide dam will fail (Casagli & Ermini, 2003) conclude that dam material size is a dominant factor in determining the long-term stability of the dam. Landslide dams caused by blockslides (e.g.Waikaremoana) usually comprise intact bedrock with large-scale fractures but no general disaggregation into fines. Seepage through a blockslide dam is often much greater than through a rock avalanche dam, and the probability of failure is much lower. The Waikaremoana dam is now the site of a hydropower development. Prior to this development the seepage through the debris was large, discharging all the lake inflow except in major storms.

CONCLUSIONS

1) The dispersive stress generated by fragmenting rock particles is equal to or greater than their unconfined compressive strength. In order to explain the runout of the Falling Mountain rock avalanche, about one particle in 200 would need to be fragmenting at any time.
2) Fragmentation takes place throughout the runout phase of rock avalanches.
3) The grain-size distribution of rock-avalanche debris has a fractal dimension corresponding to a particle arrangement that equalises and minimises the probability of fragmentation of each individual particle.
4) Low-angle rapid blockslides such as that at Waikaremoana result from low frictional resistance to block motion, due to intense fragmentation on the sliding surface generating vertical forces sufficient to support most of the weight of the block.
5) The stability of landslide dams is related to the grain-size distribution of the dam material. The relative rarity of landslide dam failures due to seepage, slumping or piping can be explained wide grain-size distribution and very small average void size of the dam material.
6) Landslide dams formed by blockslides are very much less likely to fail by overtopping than those formed of fragmented debris. Seepage through substantial cracks in the block is likely to prevent significant overtopping.

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