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Mobility of Rock Avalanches

by

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1. Introduction

Very large rockslides in strong rocks usually disintegrate into rapidly flowing masses of fragments, travelling far beyond the source scars. Such "rock avalanches" cause total destruction in their path and are important in terms of life loss and economic impact, even though they are very infrequent. This paper is a review of the problematics of predicting rock avalanche behaviour.

2. Frequency of occurrence

Cruden (1985) estimated the frequency of large rockslides in a part of Alberta, Canada, as 1 to 2 per 100 km^2 per 5,000 years. Only about 5 percent of the cases considered were major rock avalanches with volumes in the tens of millions of cubic metres. A slightly higher frequency was suggested by Gardner (1980) for a small study area in the same region.

S. G. Evans and J. J. Clague (see Evans et al., 1989) compiled historical records of rock avalanches for the entire Canadian Cordillera ; an area containing some 1,000,000 km^2 of mountainous terrain. This large region experienced 18 known rock avalanches during the last 140 years, or one every 8 years on average.

The typical annual frequency of occurrence of major rock avalanches in the Canadian Cordillera is thus of the order of 1:500 to 1:1,000 per 10,000 km^2 of mountainous area.

By comparison, volcano-related rock avalanches in the Japanese Islands occur once every 100 years, based on eight historical occurrences and 48 dated pre-historic events (T. Inokuchi, pers. Comm., 1989).

An ability to predict the area endangered by an incipient rock avalanche is important. If the area is underestimated, deaths and severe damage may occur. If it is overestimated, valuable development land will be lost. Yet, our understanding of rock avalache dynamics is still far from complete.

3. Empirical indices of rock avalanche mobility

Heim (1932) appears to have been the first to note that rock avalanches (sturzstroms) travel further, the larger their volume. In an often-quoted paper, Scheidegger (1973) formalized this observation by plotting the ratio of the maximum elevation difference (H) and the path length (L) against the volume of the slide, as shown in Fig. 1. The H/L ratio equals the tangent of the overall travel angle ("Fahrboeschung"), as defined in Fig. 2. A simple sliding block dynamic analysis due to Heim (1932) identifies the "Fahrboeschung" with an "effective friction angle" of the rock avalanche. As a result, its magnitude has been considered by many authors as a measure of mobility.

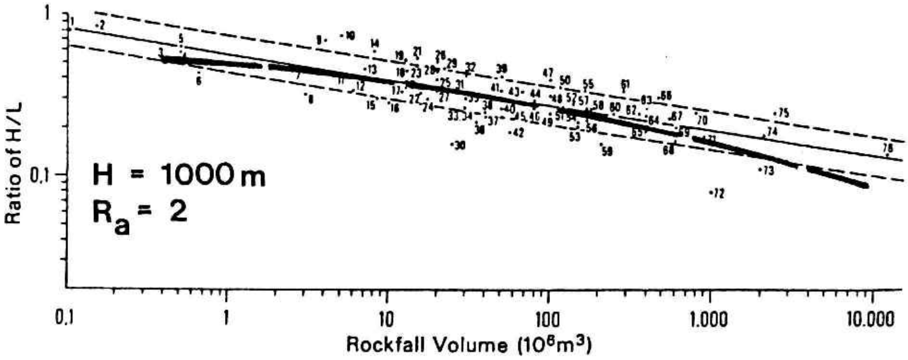

Fig. 1 Correlation between the H/L ratio (see fig. 2) and rock avalanche volume, compiled from 76 European cases by Li (1983). The bold dashed line is based on Equation (4). The thin line is the linear regression function, with standard deviation.

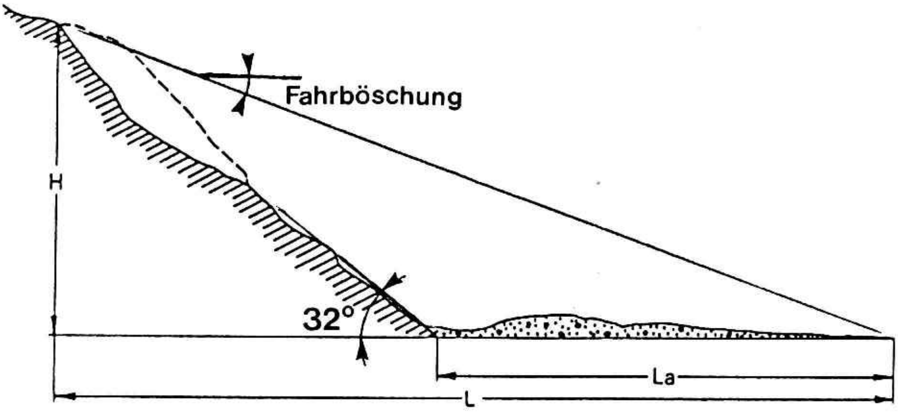

Fig. 2 A typical profile of a rock avalanche and a definition of the geometrical terms (after Li, 1983).

Hsü (1975) questioned the friction block analogy and introduced qualitative arguments to show that sturzstroms flowed like liquids to deposit in a low part of the available path profile. Under such conditions, a better measure of mobility is an "excessive travel distance", L_a, defined as the length between the distal edge of the deposit and the toe of a line projected at 32° from the source area. Again, a rough correlation of this index with the volume of the rock avalanche can be demonstrated (Fig. 3).

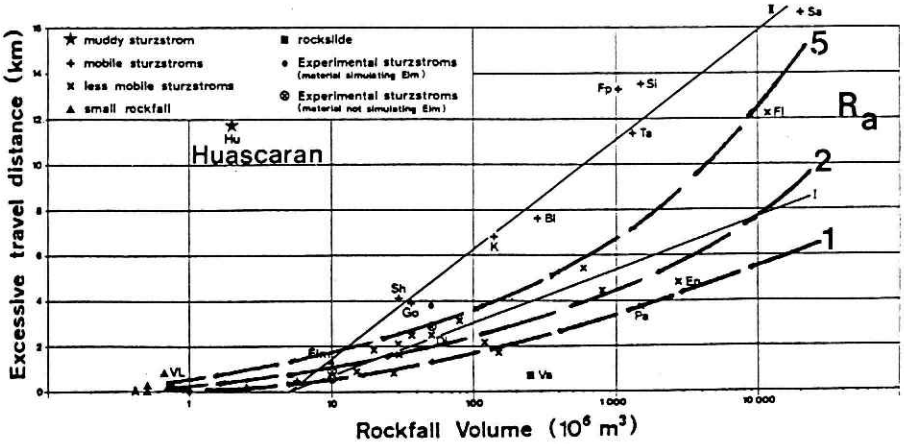

Fig. 3 Correlation between the excessive travel distance and rock avalanche volume (Hsü, 1975). The bold dashed lines correspond to Equation (3).

In the following it is shown that both of these mobility/volume relationships derive from two simple properties of rock avalanche paths :

a) Rock avalanche profiles tend to have bi-linear forms similar to that of Fig. 2, consisting of a source/travel segment inclined at 25° to 40° and a near-horizontal deposition segment.

b) There is a rough proportionality between the volume (V) of a deposit and the area (A) covered by it (or between volume and mean thickness). Such a relationship was documented by Hungr (1981, page 309), Davies (1982) and Li (1983). The latest author compiled the diagam shown in Fig. 4, yielding an empirical correlation equation :

$$\log A = 1.9 + 0.57 \log V \tag{1}$$

It is of interest to note that Eqn. (1) is similar to a mathematical relationship derived from an assumption of a constant form, where A is related to 0.67 power of V (see bold dashed line in Fig. 4).

The deposit area can be expressed as the product of the length of the deposit (L_a) and the mean width (B) :

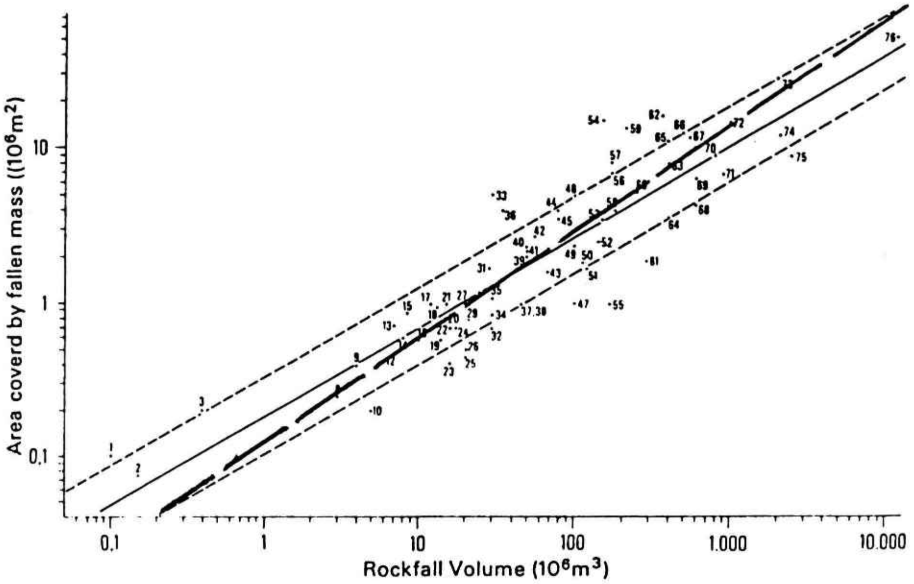

Fig. 4 Correlation between the areas covered by rock avalanche deposits and their volumes (Li, 1983). The thick dashed line represents a relationship derived from an assumption of similarity of form.

$$A = L_a B = L_a^2 R_a \tag{2}$$

Where R_a is a length to width (aspect) ratio of the deposit.
Substituting from (2) to (1) and solving for L_a :

$$L_a = R_a 10^{(0.95+0.28 \log V)} \tag{3}$$

Assuming, as expressed under a) above, that a typical rock avalanche profile is geometrically similar to Fig. 2, then L_a equals the excessive travel distance as defined by Hsü (1975). The dashed lines of Fig. 3, representing Eqn. (3) evaluated for aspect ratios of 1 to 5, indeed encompass most of the plotted points. Similar lines were derived by Hungr (1981, p. 351). The Huascaran example lies far outside the trend, because its profile is gradual, not bi-linear. The wide scatter of the remaining points can similarly be explained by the differences of the profiles from the ideal represented by Fig. 2. Path confinement, as reflected in the aspect ratio, is also important.

The H/L ratio can be derived from the geometry of Fig. 2 as :

$$\frac{H}{L} = \frac{H}{H\cot 32^\circ + L_a} \tag{4}$$

Where L_a is expressed by Eqn. (3). Substituting an H of 1,000 m and an R_a of 2.0 yields the bold dashed line of Fig. 1, which falls close to the correlation line of the data set. A similar relationship was shown by Davies (1982).

In summary, correlations of the equivalent friction angle and the excessive travel distance with volume do not document a systematic increase in mobility. Instead, as suggested by Hsü (1975), they are a consequence of a fluid behaviour which prevails with volumes beyond a few millions of m^3, but is otherwise unrelated to volume.

4. Mobility theories

A number of authors have attempted to explain the mechanism of rock avalanche movement, some in terms of the equivalent friction angle and others in terms of a transition to fluid-like behaviour :

1) Air cushion theory. Shreve (1966, 1968) suggested that a sheet of rockslide debris slides on a cushion of air, trapped when the slide is catapulted into an air trajectory by a ramp. He presented an interpretation of certain features of deposit morphology to support the idea. Some of this interpretation has been questioned by Hsü (1975) and Cruden and Hungr (1986). Furthermore, Voiglit (1978) questioned the air entrapment mechanism and Howard (1973) described apparently highly mobile rock avalanches on the airless moon.

2) Fluidization by trapped air (Kent, 1966, Krumdieck, 1984). A similar air entrapment process is thought to cause a full or partial fluidization of the debris, by means of upward flow of air. The concept of airfoil lift was introduced by Krumdieck (1984), but questioned by Hungr and Morgenstern (1985). Lack of physical evidence for fluidization was pointed out by Hungr (1981), Cruden and Hungr (1986) and Cassie et al. (1988).

3) Fluidization by vapor. Pautre et al. (1974) and Habib (1975) demonstrated that rock avalanche movement expends sufficient energy to vaporize pore water. The heat calculations require important assumptions concerning the thickness of the shearing zone. Also, the influence of rock mass expansion during breakage upon pore gas pressure has not been clarified.

4) Rock melting. Erismann (1979) found specimens of molten rock near the sliding surface of a rockslide near Koefels, Switzerland. He showed that sufficient frictional heat can be produced in exceptionally thick slide masses to melt basic igneous rock and showed a corresponding reduction of the friction angle in experiments.

5) Rock dissociation. Many mobile rock avalanches occurred in calcareous rocks, which do not melt when heated. Erismann (1979) suggested that such landslides may be fluidized by escaping CO_2 gas, produced by heat dissociation of limestone.

6) Fluidization by dust dispersions. Hsü (1975) proposed that dense dispersions of

rock dust act as a pore fluid among the larger clasts. The role of air in the behaviour of the dispersions was neglected, as the phenomenon was assumed to occur in the moon avalanches as well as in the terrestrial ones. Hungr and Morgenstern (1984b) showed by experiment that rock dust and sand mixtures behave frictionally, with no velocity dependence.

7) Mechanical fluidization. This hypothesis seems to have never been rigorously defined, although many authors have alluded to it (Howard, 1973, Scheidegger, 1975, Hsü, 1975, Koerner, 1977, Voight, 1978, McSavenney, 1978, Davies, 1982 and others). The underlying idea is that the mechanical character of shearing in a granular material changes at very high strain rates, as the grain to grain contacts change from continuous sliding to intermittent collisions. No one has succeeded so far in demonstrating a change of behaviour theoretically.

Laboratory experiments including flume tests at velocities of up to 6 m/sec and ring shear tests at 1 m/sec failed to show any indication of a change of behaviour with increasing strain rate (Hungr, 1981, Hungr and Morgenstern, 1984 a, b, Sassa, 1984, Moriwaki, 1987). It may be argued that still higher velocities are required to demonstrate a change in behaviour. However, in both types of test, the shearing was concentrated in a zone less than 20 mm thick, producing a shear strain rate of 5,000 to 30,000 % per sec. Such a strain rate would yield a flow velocity of 25 to 150 m/sec (90 to 540 km/hour) in a shear zone only 1 m thick.

8) Acoustic fluidization. Melosh (1979) showed theoretically that vibrations produced on the sliding surface by rapid movement over uneven ground could reduce the dynamic friction angle of the granular debris. Direct shear tests of sand conducted on a vibrating table, described by Barkan (1962), showed that such a phenomenon does exist. Barkan (1962) even describes measurements of fluid behaviour characterized by a "vibro-viscosity".

An important difference between mechanical and acoustic fluidization must be pointed out. The former process is thought to be inherent to the material itself and requires no energy input other than vigorous shearing. It should therefore be capable of duplication in the laboratory. Acoustic fluidization, on the other hand, requires vibrational energy generated externally by the boundary conditions of the full scale movement.

9) Lubrication by liquefied saturated soil. Heim (1932) explained the high mobility of the Elm Slide by the effects of mud, entrained by the rockslide from loose valley deposits, liquefied under the weight of debris. A similar mechanism was suggested by Sassa (1984), described with the use of pore-pressure parameters, and incorporated into a dynamic model. Hutchinson (1987) and De Matos (1987) developed related models, including the effects of consolidation. No existing model accounts for the velocity dependence of pore-pressure in the liquefied layer, which may introduce important rheological effects.

A "splash" of liquid fine grained soils has been noted at the margins of many rock avalanche deposits (e. g. Cruden and Hungr, 1986). A notable case is the Hope

Slide in British Columbia, Canada, in which the area covered by muddy splash deposits is as large as the area of the rock debris itself (Fig. 5). It is of interest that a comparison of pre-slide and post-slide topography by Bruce and Cruden (1977) yielded a puzzling deficit of material in the deposition area, possibly due in part to the displacement of underlying valley fill.

Strong entrainment of valley floor and slope deposits was also documented from the upper part of the path of the 1984 Ontake rock avalanche in Japan (Inokuchi, 1985). Extremely long displacements and flow of strong granular rock waste from mine waste dumps in south eastern British Columbia (Campbell, 1973) can also best be explained by liquefaction of loose saturated colluvial soil in the path of the flow, as these failures lack the pre-requisites for any of the other mechanisms.

Fig. 5 Deposit of the 1965 Hope Landslide in British Columbia, Canada. The dark area in the forefront is the "splash" of liquefied valley deposits displaced by the rock avalanche. (B. C. Government Airphoto BC (0) 447).

5. Discussion

Probably each of the mechanisms listed above plays a certain role in the mobilization of rock avalanches. It remains difficult to decide which is the dominant mechanism in a specific case and how it controls the dynamics of the flow.

The weight of the evidence introduced in the works cited in the previous section seems to favour lubrication by liquefied material (Hypothesis 9). This mechanism is clearly dominant in some cases and possible in all, except for the lunar examples.

Acoustic fluidization (8) has a sound theoretical and experimental basis and is not contradicted by the field evidence.

The group of theories based on gas pressure (1, 2, 3 and 5) appear plausible on theoretical grounds, but are not well supported by field evidence. For example, inverse grading which is common in rock avalanche deposits points to the occurrence of vibrations, not to gas fluidization which would produce a normal grading. Also, gas escape structures such as craters, marginal fans or channelling structures have not been described in the rock avalanche literature.

The mechanical fluidization theory (7) has been disproven by experiments and should be replaced by the acoustic fluidization concept.

The two most plausible explanations of rock avalanche movement (8 and 9) both depend on the structure and the boundary conditions of the full scale flow, as much as on material properties. This makes mechanical modelling exceedingly difficult. An empirical approach has a greater chance of success.

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References

Barkan, D. D. (1962) : Dynamics of bases and foundations. Mc. Graw Hill, New York, 400pp.

Bruce, I. and Cruden, D. M. (1977) : The dynamics of the Hope Slide. Bulletin, Int. Assoc. Engineering Geology, No. 16, 94-98.

Campbell, D. B. (1978) : Performance of a waste rock dump on moderately or steeply sloping foundations. Procs., Symposium on the Stability in Coal Mining, Can. Inst. of Mining, Vancouver, 395-405.

Cassie, J. W., VanGassen, W., and Cruden, D. M. (1988) : Laboratory analog for the formation of molards- cones of avalanche debris. Geology, Vol. 16, 735-738.

Cruden, D. M. (1985) : Rock slope movements in the Canadian Cordillera. Can. Geotech. Journ., Vol. 22, 528-540.

Cruden, D. M. and Hungr, O. (1986) : The debris of the Frank Slide and theories of rockslide-avalanche mobility. Can. Journ. of Earth Sciences, Vol. 23, 425-432.

Davies, T. R. H. (1982) : Spreading of rock avalanche debris by mechanical fluidization. Rock

Mechanics, Vol. 15, 9-24.

DeMatos, M. (1987) : A sliding consolidation model for rock avalanches. Ph. D. Thesis, Univ. of Alberta, Edmonton, 350pp.

Erismann, T. H. (1979) : Mechanism of large landslides. Rock Mechanics, Vol. 12, 15-46.

Evans, S. G., Clague, J. J., Woodsworth, G. J. and Hungr, O. (1989) : The Pandemonium Rock Avalanche, British Columbia. Can. Geotech. Journ., Vol. 26, No. 3, 427-446.

Gardner, J. S. (1980) : Frequency, magnitude and spatial distribution of mountain rockfalls and rockslides in the highwood Pass area, Alberta, Canada. In Thresholds in Geomorphology, Coates, D. R. and Vitek, J. D., Eds., Allen and Unwin, London, 267-295.

Habib, P. (1975) : production of gaseous pore pressure during rock slides. Rock Mechanics, Vol. 7, 193-197.

Heim, A. (1932) : Bergsturz und Menchenleben. English translation by N. Skermer, BiTech Publishers, Vancouver, 195 pp.

Howard, K. (1973) : Avalanche mode of motion : implications from lunar examples. Science, Vol. 180, 1052-1055.

Hsü, K. J. (1975) : Catastrophic debris streams (sturzstroms) generated by rockfalls. Bull., Geol. Soc. of America, Vol. 86, 129-140.

Hungr, O. (1981) : Dynamics of rock avalanches and other types of slope movements. Ph. D. thesis, Univ. of Alberta, Edmonton, 500 pp.

Hungr, O. and Morgenstern, N. R. (1984a) : Experiments on the flow behaviour of granular materials at high velocity in an open channel. Geotechnique, Vol. 34, 405-413.

Hungr, O. and Morgenstern (1984b) : High velocity ring shear tests on sand. Geotechnique, Vol. 34, 415-421.

Hungr, O. and Morgenstern, N. R. (1985) : Discussion reply. Geotechnique, Vol. 35, 384-385.

Hutchinson, J. N (1987) : A sliding-consolidation model for flow slides. Can. Geotech. Journ., Vol. 23, 115-126.

Inokuchi, T. (1985) : The Ontake rock slide and debris avalanche caused by the Naganoken-Seibu earthquake, 1984. proscs., 4th Int. Conference and Field Workshop on Landslides, 1985, Tokyo, 329-338.

Kent, P. E. (1966) : The transport mechanism in catastrophic rock falls. Journ. of Geology, Vol. 74, 79-83.

Koerner, H. J., (1977) : Flow mechanism and resistances in the debris streams of large rock slides. Bull., Int. Assoc. of Engineering Geology, No. 16, 101-104.

Krumdieck, A., (1984) : On the mechanism of large landslides. Procs., 4th Int. Symposium on Landslides, Toronto, Vol. 1, 539-544.

Li, T. (1983) : A mathematical model for predicting the extent of a major rockfall. Zeitschrift fur Geomorphologie, Vol. 24, 473-482.

McSavenney, M. J. (1978) : Sherman Glacier Rock Avalanche, Alaska. In Rockslides and Avalanches, Voight, B., Editor, Elsevier, Vol. 1, 197-258.

Melosh, H. J. (1979) : Acoustic fluidization : a new geologic process ? Journ. of Geophysical Research, Vol. 84, 7513-7520.

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岩屑流の流動機構について

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要　旨

大規模岩盤地すべりは崩壊時に急速に流動化し，長距離を流下する(岩屑流)ことが多い．この岩屑流は流下経路上にある住家や橋梁などをすべて破壊し，甚大な人的，物的被害をもたらす．本稿はこの岩屑流発生の特徴ならびに流動機構について検討したものである。

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*注：筆者は昭和63年度科学技術庁科学技術振興調整費　重点基礎研究課題「崩壊土砂の流動化機構に関する実験的研究」の外国人招へい費により，平成元年2月1日より同3月31日まで防災科学技術研究所(旧，国立防災科学技術センター)に滞在し，共同研究を行った．