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On the Prediction of the Reach and Velocity of Catastrophic Landslides

By

Adrian E. Scheidegger

With 2 Figures

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Zusammenfassung — Summary — Résumé

On the Prediction of the Reach and Velocity of Catastrophic Landslides. An analysis of the data of rapid, catastrophic landslides shows that a correlation exists between the logarithm of the volume V of such landslides and the logarithm of the coefficient of friction f which governs their course. This correlation is

$$_{10}\log f = -0.15666\ _{10}\log V + 0.62419$$

where the volume is in m^3. The coefficient of correlation is 0.82. This correlation can be used to predict the reach and the velocity of an imminent landslide, if the volume can be estimated beforehand.

Über die Vorhersage von Reichweite und Verlauf katastrophaler Bergstürze. Eine Analyse der Beobachtungen von schnellen, katastrophalen Bergstürzen zeigt, daß eine Korrelation zwischen dem Logarithmus des Volumens V und dem Logarithmus des Reibungskoeffizienten f, der ihren Verlauf bestimmt, existiert. Diese Korrelation hat die Form

$$_{10}\log f = -0{,}15666\ _{10}\log V + 0{,}62419$$

wo das Volumen im m^3 gemessen wurde. Der Korrelationskoeffizient beträgt 0,82. Diese Korrelation kann dazu verwendet werden, um die Reichweite und den Verlauf eines erwarteten Bergsturzes vorauszusagen, wenn dessen mutmaßliches Volumen abgeschätzt werden kann.

Sur la prédiction de la portée et du cours d'éboulements catastrophiques. Les observations des éboulements rapides et catastrophiques qui sont rapportées dans la littérature sont analysées. Il est démontré qu'une corrélation existe entre le logarithme du volume V de ces éboulements et le logarithme du coefficient de la friction qui gouverne leur cours. Elle est

$$_{10}\log f = -0{,}15666\ _{10}\log V + 0{,}62419$$

où le volume est mesuré en m^3. Le coefficient de la corrélation est 0,82. Cette corrélation peut être utilisée pour prédire l'extension et la vélocité d'un éboulement imminent si son volume est estimable en avance.

A. Introduction

The rapid motion of a small mass down a scree slope is governed by the laws of dry friction. The coefficient f of such friction is close to the tangent of the angle of repose of the sliding debris mass which, in turn, is equal to the angle of internal friction ϕ (in the Coulomb-Mohr sense) of the material in question. Hence, as can be easily shown, the downhill motion of a debris mass is independent of its size, because this mass drops out of the equations of motion.

In a model based on friction, the total vertical height of the path of the landslide divided by the total horizontal reach represents nothing but the average coefficient of friction f, provided the slide started from rest. This had already been noted by Heim (1932). The deduction of this fact is evident

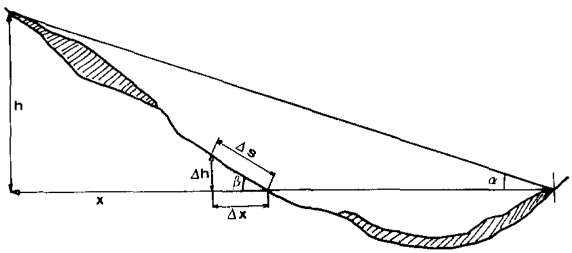

Fig. 1. Geometry of a landslide
Geometrie eines Bergsturzes
Géometrie d'un éboulement

from an inspection of Fig. 1, which represents a case somewhat more general than that considered by Heim. Accordingly, if a mass m slides through the distance Δs, the energy principle requires

$$\Delta\, (^1/_2\, m v^2) = \text{mg}\, \Delta s \sin\beta - \Delta s\, \text{mg}\, f \cos\beta,$$

where v is the sliding velocity and the meaning of the other symbols becomes evident from an inspection of Fig. 1. Now, the following relations hold

$$\Delta s \sin\beta = \Delta h; \quad \Delta s \cos\beta = \Delta x$$

whence

$$\frac{1}{g}\Delta\, (^1/_2\, v^2) = \Delta h - f\, \Delta x.$$

If we integrate the last equation from $s=0$ to $s=$total course of the slide, assuming that the slide started from rest and is at rest at the end, we get

$$0 = h - f x$$

or

$$f = h/x = \tan\alpha.$$

The above calculations have to be modified in an obvious fashion if the slide does not start from rest but is, e. g., triggered by a rock fall. Then an initial velocity v_0 has to be introduced into the equations.

According to the model used, it is evident that the rock mass, the average velocity and the local slope angle β all drop out of the final equations. The characteristic parameter is solely the coefficient f which should determine the angle α and therewith, if h is known, the reach x. Since, by theory, the coefficient f should be equal to the angle of repose of the sliding material, it ought to be possible to estimate the reach of a slide from these quantities. This method works indeed well for small slides on scree slopes and has been tested for rock falls of up to some tens of thousands of cubic meters in volume.

However, it is a well known fact that for large, catastrophic landslides, the coefficient of friction becomes progressively smaller as the volume of the sliding mass increases, if one maintains a simple frictional model. Heim (1932) has already mentioned this fact and Scheller (1970) has plotted empirically tan α against the logarithm of the volume of the slides and obtained a vague curved correlation. He then conjectured that the velocity of the slides increases with their volume, and that the friction decreases with the velocity, either like a square exponential [exp $(-\text{const. } v^2)$] or like a hyperbola [$1/(\text{const. } v + 1)$]. Based upon these assumptions, he attempted to set up correlations. His calculations became very involved and the final formulas cannot be written in closed form; they contain a number of parameters. It seemed therefore indicated to try to find some simpler correlations for the possible prediction of the reach of an anticipated landslide.

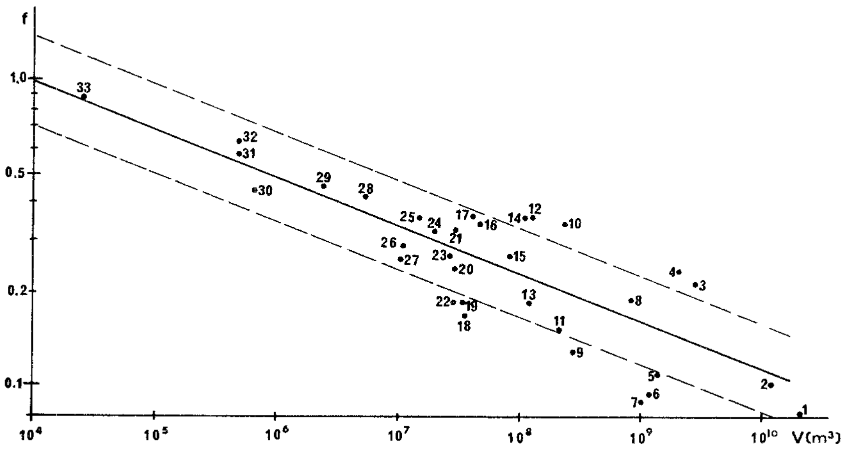

Fig. 2. Correlation between landslide volume V (in m³) and the coefficient of friction f. The dotted lines represent the standard deviation of the data from the correlation line. The numbers correspond to the number of the landslide in the Table

Korrelation zwischen dem Bergsturzvolumen V (in m³) und dem Reibungskoeffizienten f. Die punktierten Linien entsprechen der Normalstreuung der Beobachtungen von der Korrelationsgeraden. Die Zahlen entsprechen den Nummern der Bergstürze in der Tabelle

Corrélation entre le volume V (en m³) d'un éboulement et le coefficient de la friction f. Les lignes ponctuées représentent la déviation normale des observations de la ligne de corrélation. Les chiffres correspondent aux nombres de l'éboulement dans la table

B. The Data

In the Table 1, we list a series of landslide data that were collected from the literature. Many of these data were already used by Scheller (1970); our Table contains a few more; it contains also the meagre data on the average velocity of the slides which were available. These velocities, however, were usually inferred ex post facto. Heim (1932) noted that the velocity depends

Table 1. Landslide Data

No.	Place	Year	Volume ($10^6 m^3$)	f	v (m/sec)	Author
1	Saidmarreh Iran	preh.	20000	0.08		Harrison & Falcon 1938
2	Flims	preh.	12000	0.13		Heim 1932
3	Engelberg	preh.	2500—3000	0.22		Arbenz 1913
4	Pamir	1911	2000	0.24		Harrison & Falcon 1938
5	Siders	preh.	1000—2000	0.14		Heim 1932
6	Tamins	preh.	1300	0.095		Scheller 1970
7	Fernpass	preh.	1000	0.09		Abele 1964
8	Glärnisch	preh.	800	0.25		Heim 1932
9	Blackhawk	preh.	280	0.13	118	Shreve 1968
10	Vajont	1963	250	0.34	25	Müller 1968
11	Silver Reef	preh.	220	0.13		Shreve 1968
12	Poschiavo	preh.	150	0.36		Heim 1932
13	Kandertal	preh.	140	0.19		Heim 1932
14	Obersee (GL)	preh.	120	0.36		Heim 1932
15	Scima da Saoseo	preh.	80	0.27		Heim 1932
16	Diablerets	1714/49	50	0.34		Heim 1932
17	Hope B. C.	1965	47.3	0.37		Mathews & McTaggart 1969
18	Gros Ventre	1925	38	0.17	46	Alden 1928
19	Goldau	1806	30—40	0.19		Heim 1932
20	Frank	1903	30	0.25	49	Daly et al. 1912
21	Voralpsee	preh.	30	0.33		Heim 1932
22	Sherman	1964	30	0.19		Shreve 1966
23	Madison Canyon ...	1959	29	0.27	45	Hadley 1959
24	Corno di Dosté	preh.	20	0.32		Heim 1932
25	Disentis	1683	10—20	0.36		Heim 1932
26	Little Tahoma Pk. ..	1963	11	0.29		Crandell & Fahnestock 1965
27	Elm	1881	10—11	0.26	42	Heim 1932
28	Wengen	preh.	5—6	0.42		Altmann 1959
29	Wengen S.	preh.	2—3	0.45		Altmann 1959
30	Val Lagone	1486	0.5—0.8	0.44		Heim 1932
31	Schächental	1887	0.5	0.58		Heim 1932
32	Airolo	1898	0.5	0.64		Heim 1932
33	Lecco	1969	0.03	0.88		

simply on the shape of the trajectory of the landslide, i. e. on the energy content available at each point of its path according to the frictional model. The velocity value given for the Elm slide given by Heim (1932) is based upon eyewitness accounts and fits with that calculated from the frictional model. The value for the Vajont slide seems to be fairly well substantiated (Müller 1968). The Elm and Vajont data represent a contradiction of any contention that there is an increase of the velocity with volume. Therefore, Scheller's (1970) assumption of a correlation between velocity and volume does not seem to be borne out by the data.

This leaves one with the suspicion that there might be a *direct* correlation between slide volume and the coefficient of friction. In order to investigate this possibility, we plotted the data of the Table on a log-log scale (Fig. 2). It is immediately obvious that the points lie reasonably close to a straight line. Thus, it is evident that this phenomenological correlation can be used to construct a prediction curve for the expected reach of an imminent slide.

C. The Prediction Curve

The volume of a potential landslide can often be estimated. The evident correlation between this volume V and the coefficient of friction f, then, allows one to calculate the expected reach of the slide. If the slide is triggered by a rock fall, the frictional model still works, but the initial velocity is then not equal to zero.

The prediction curve is shown in Fig. 2, which gives the correlation line between the coefficient of friction f and the volume V of the slides, as calculated by the standard least squares regression method (applied to the logarithms of the data). Analytically, this straight line has the form

$$\log f = a \log V + b.$$

One finds, if V is in m^3 and the logarithms are to the basis 10

$$a = -0.15666, \quad b = 0.62419.$$

The correlation coefficient is 0.82. The dotted lines in Fig. 2 represent the standard deviation of the data from the correlation line

$$\sigma_{\log f} = 0.14298.$$

The probability that in a particular case the actually found value of f falls inside the dotted lines is, as is well known, equal to 0.6827.

The "prediction curve" must be cut off at the top by the value of

$$f = \tan \phi,$$

where ϕ is the angle of repose of the debris material involved. Most angles of repose are around 30—40°, hence $\tan \phi = 0.57$—0.83. The decrease of the coefficient of friction with volume, therefore, has to be taken into account when the volume of the slide approaches and exceeds 100000 m^3. Below this volume, a constant coefficient of friction may be assumed in most cases.

Thus, the reach and the velocity of an expected landslide can be estimated by the use of a frictional model with the coefficient of friction being calculated by the method indicated above.

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Anschrift des Verfassers: Prof. Dr. A. E. Scheidegger, Institut für Geophysik, Technische Hochschule, A-1040 Wien, Karlsplatz 13, Austria.