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Rock avalanche runout prediction using a dynamic model

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ABSTRACT: A general dynamic model was used to back-analyse 23 case histories of rock avalanches. Three alternative rheologies were tried: frictional, Voellmy (frictional/turbulent) and Bingham. The two-parameter Voellmy rheology gave the best results in terms of debris spreading and velocity distribution.

1. INTRODUCTION

Major rockslides in mountainous areas often develop into rapidly moving streams of debris, travelling over long distances and causing total and sudden destruction of fairly large areas. Such landslides are known as rock avalanches or, using a German term originating in the Alps, *stuerzstroms* ("collapse streams").

When the potential for rock avalanche occurrence is recognized, it is necessary to delineate the hazard area, so that appropriate planning decisions can be made. This article describes a research project whose objective is to develop an analytical method of predicting rock avalanche runout, which can be applied in hazard studies.

Existing methods of rock avalanche runout prediction rely on simple empirical relationships, such as correlations between the avalanche volume and the angle of travel (*fahrboeschung*), or volume and the distance of reach. Their serious drawback is lack of precision, which results from the complexity of the processes involved in rock avalanche motion.

Analytical prediction methods have been receiving increased attention from researchers in recent years. A brief recent review can be found in Hungr (1995).

The microcomputer model DAN (dynamic analysis) has been developed specifically for simulating the motion behaviour of flows, flow slides and avalanches. The theory of the model and the results of testing against controlled experiments are given in Hungr (1995).

2 RHEOLOGICAL MODELS

DAN is a numerical solution of the equations of motion, formulated in terms of an open rheological kernel. The selection of the applicable rheology for any type of landslide is made on the basis of back-analysis. Following our prior experience with the program, three rheologies were selected for detailed study:

Frictional rheology: The resisting shear forces at the base of the flowing mass are assumed to depend only on the effective normal stress, i.e. they are independent of velocity. This assumption implies that the vertical velocity profile is indeterminate. In general, however, it is expected that shear strains will be concentrated in a narrow zone at the base of the flow, where the material is finest and where saturation and pore-pressure may exist.

The frictional model as used in DAN has only one parameter, the "bulk friction angle" ϕ, which is related to the effective dynamic friction angle ϕ' through the use of a pore pressure ratio, r_u:

$$\phi = \arctan [\tan \phi' (1-r_u)] \quad (1.1)$$

The effective dynamic friction angle of loose granular debris equals approximately 32 degrees. Full saturation (without excess pore-pressure) would produce a bulk friction angle of about 17 degrees. Lower values of the angle imply the existence of partial liquefaction at the base of the slide mass.

Voellmy rheology: This two-parameter model was developed by Voellmy (1955) for use in lumped-

Table 1
Best fit parameters for back-analyses.

No.	Case	Frictional	Bingham		Voellmy	
		Bulk Friction Angle (deg)	Yield Strength (kPa)	Viscos-ity (kPa.s)	Friction Coeff.	Turbu-lence Coeff. (m/s2)
1-1	Pandemonium Ck.	13	-	-	0.1	1000
1-2	Frank	16	100	10	0.1	700
1-3	Avalanche Lake N.	10	200	10	0.1	700
1-3a	Avalanche Lake S.	11	200	10	0.1	500
1-5	Hope	18	200	10	0.1	500
1-6	Dusty Creek	21	100	10	0.2	200
1-8	Rubble Creek	13	-	-	0.07	100
1-9	Turbid Creek	17.5	-	-	0.1	300
1-10	Kennedy River	23	50	10	0.1	300
1-11	Mystery Creek	17	90	9	0.1	600
1-12	Lake of the Woods	20	200	10	0.24	200
2-1	Mt. St. Helens	9.5	278	50	0.08	500
2-2	Madison Canyon	16	100	20	0.2	500
2-3	Sherman Glacier	10	16	1.6	0.03	1000
2-4	Gros Ventre	16	140	14	0.22	500
3-1	Val Pola	16	150	30	0.1	500
3-2	Mt. Granier	12	80	10	0.09	1000
3-4	Diablerets	20	400	40	0.2	450
3-5	Elm	14	100	10	0.14	500
3-6	Goldau	12	100	10	0.1	500
3-8	Flims	23	-	-	0.21	500
4-1	Ontake	8	-	-	0.03	200
5-3	Mayunmarca	12	100	10	0.1	500

Note: missing values denote cases where convengence of the model could not be reached.

mass modelling of snow avalanches. Its use for rock avalanches was suggested by Koerner (1976). The model contains a friction coefficient, μ, which is equivalent to tan ϕ in (1.1) above. Added to this is a "turbulent" term, dependent only on the square of the flow velocity and the density of the debris.

Voellmy (1955) introduced the second term to summarize all velocity-dependent factors of flow resistance. In rock avalanches, they may arise from undrained pore-pressure changes due to dilatancy in a thin liquefied layer at the base of the flow.

Bingham Model: The Bingham model has been used for rock avalanche analysis by Sousa and Voight (1991) and others. The resisting shear stress depends on a constant yield shear strength and a viscous term dependent on the velocity and the inverse of the thickness of the debris sheet.

The above properties of the three models have bearing on the behaviour of the simulated cases. The evaluation of the merits of each model depends on its ability to simulate observed behaviour of actual landslides.

3. BACK-ANALYSES

A compilation of literature and other available data resources has been completed (Hungr and Evans, 1995, unpublished data) and 23 well documented case histories suitable for back-analysis were selected (Table 1).

Each of the case histories listed in Table 1 was analysed in three dimensions using each of the three alternative rheological models. The main results of each trial analysis were systematically recorded on result sheets. Each trial run was assessed by matching the following parameters to the actual values as determined from maps or from reports of the case histories: total horizontal runout distance, length of the main deposit, mean thickness of debris in up to three locations, flow velocities (where available) and flow duration.

Apart from the first two, the above parameters could not always be obtained from the case history records. The comparisons were therefore carried out opportunistically, wherever data was available. In case of the frictional model which has only one parameter, only the total runout distance was used. For the two-parameter Voellmy and Bingham models, pairs of parameters were sought to produce the correct runout, while at the same time obtaining the best possible match in terms of velocities and duration.

The best match parameters for the three models are summarized in Table 1. Example results for the Frank Slide are shown in Figure 1.

Only the rheological parameters were varied. The remaining variables, held constant in all the analyses, were: bulk unit weight of the debris, 20 kN/m^3, coefficient of lateral pressure "at rest" 1.0, active lateral pressure coefficient 0.33, passive 3.0.

4. EVALUATION OF RESULTS

4.1 *Influence of Rheology*

The first criterion used to evaluate the influence of rheology was to compare the calculated and actual length of the main deposit. The results are shown in Figures 2,3 and 4 for the three models.

The performance of the frictional model (Figure 2) is somewhat erratic. Some of the calculations are as much as 50% too short (3-6, Goldau), others too long as a result of accumulation of debris in the upper part of the path. In general, the debris distribution tends to thin fronts and thick proximal parts for the frictional model. This was actually reported in some of the cases (3-5, Elm), but generally the actual debris distribution shows the opposite trend.

The Voellmy model (Figure 3) performs quite well, except for several notable exceptions.

The Bingham model (Figure 4) consistently overestimates the debris length. It predicts deposition even on steep slopes close to the rockslide source area, which often conflicts with observations.

A second criterion for comparing the results of modelling with actual observations is in terms velocity and flow duration. Figure 5 plots the calculated velocity values against observed velocities. In those cases where more than one velocity estimate is available, only the observation nearest the mid-point of the path length was selected to avoid possible bias. The three lines plotted on Figure 5 give the linear regression analyses of the plotted points.

The Voellmy models give excellent correspondence between the calculated and observed velocities. Both the frictional and Bingham models overestimate the velocities. This trend was previously noted for the frictional model by Koerner (1976). A comparison in terms of flow duration produced a similar result.

4.2 *Predictive Performance*

The above results show that we can model past events with reasonable accuracy by finding the matching parameters through trial and error. However, it is still difficult to produce predictions of the most likely runout beforehand.

An attempt at using pre-determined material properties is shown in Figure 6. The total runout distance calculated using the Voellmy model, with the friction coefficient set to a constant 0.1 (bulk friction angle 5.7 degrees) and the turbulence coefficient of 500 m/sec^2 are compared with the actual runout distances. The resistance parameters are within the range found applicable by Koerner (1976). Of the 23 cases analysed, 16 (70%) result in a prediction which is within about 10% of the actual runout (as shown by line limits in Figure 6).

Only two of the remaining events are under-predicted: 2-3 (Sherman Glacier), an event which moved almost entirely over snow-covered glacier and 4-1 (Mt. Ontake), an event which entrained a large proportion of weathered saturated soils and assumed the character of a large fluid debris flow.

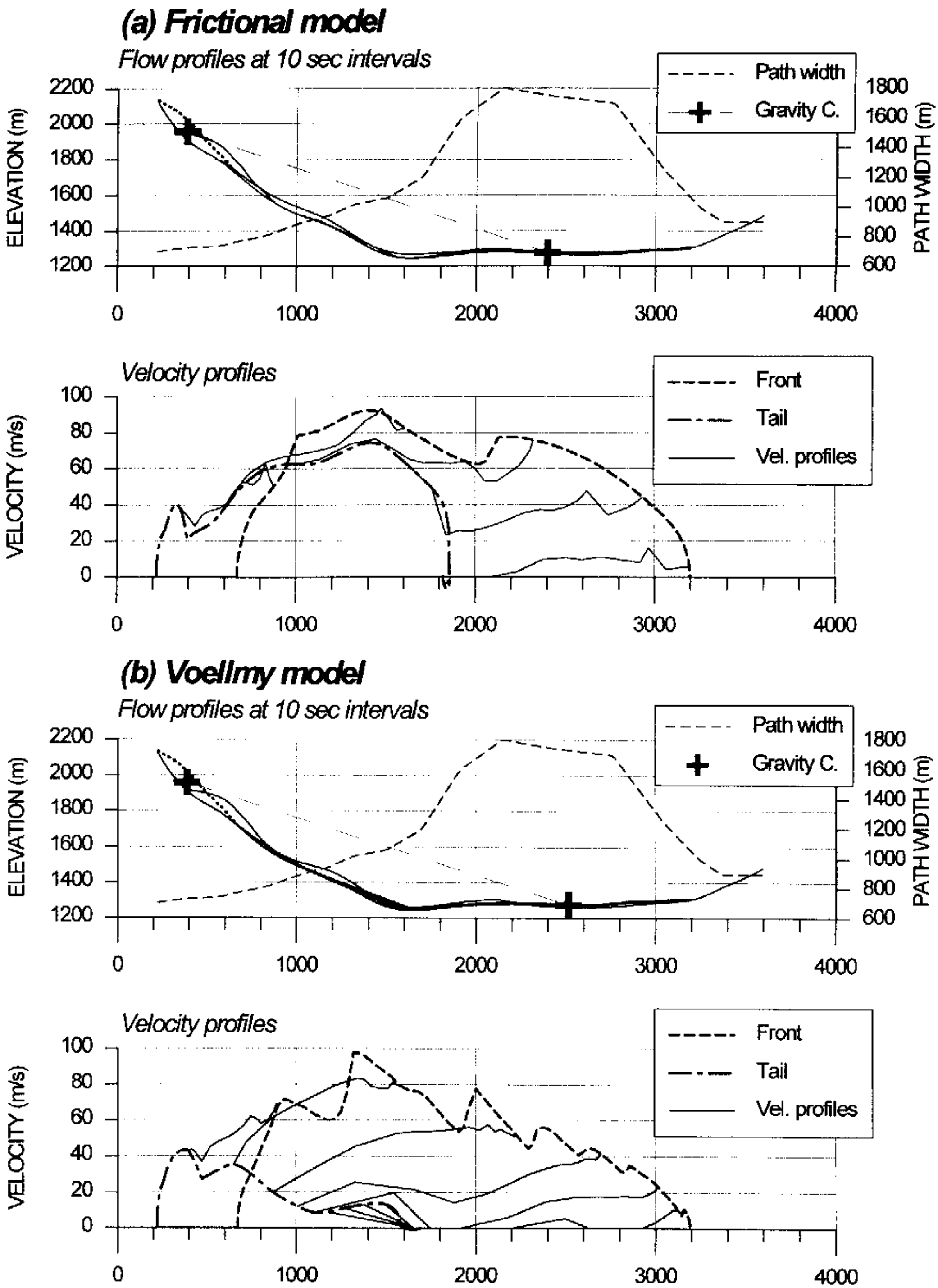

Figure 1. Example analyses of the Frank slide, Alberta, Canada

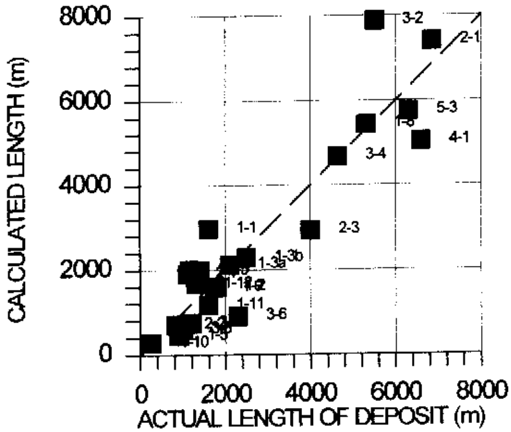

Figure 2
Deposit length prediction, frictional model

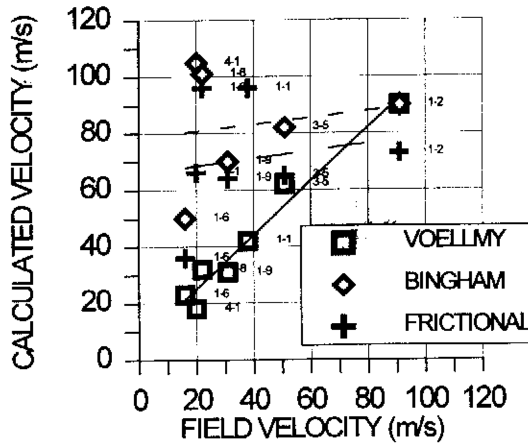

Figure 5
Flow velocity predictions

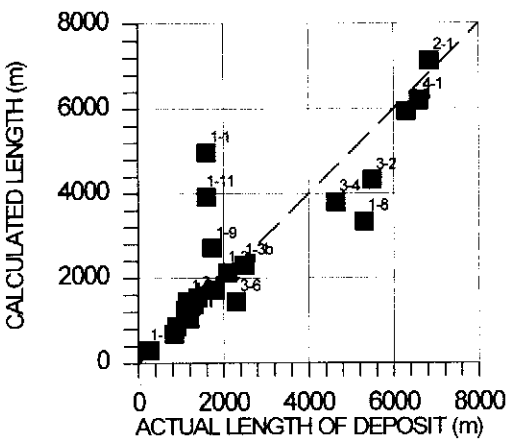

Figure 3
Deposit length prediction, Voellmy model

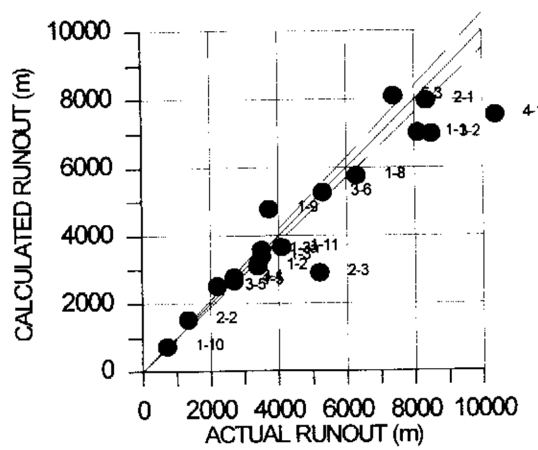

Figure 6
Runout distance prediction, Voellmy model with a μ of 0.1 and ξ of 500 m/s^2

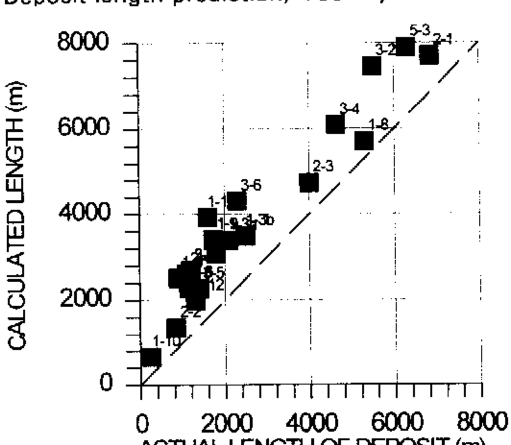

Figure 4
Deposit length prediction, Bingham model

The runout is overpredicted in five events: 1-6 (Dusty Creek), 1-12 (Lake of the Woods), 2-4 (Gros Ventre), 3-4 (Diablerets) and 3-8 (Flims). The common characteristic of these events is possibly a lack of saturated soils in the flow path, but this is a subject of continuing study.

5. CONCLUSIONS

The dynamic model DAN is capable of simulating the main features of all the rock avalanche cases analysed, despite their great range of types and magnitudes.

Of the three rheologies considered, the Voellmy model produces the most consistent results in terms of debris spreading and distribution as well as velocity data.

The main deficiencies of the frictional model are the tendency to predict excessive thinning of the deposits in the distal part and to overestimate velocities.

The Bingham model tends to exaggerate the degree of longitudinal spreading of the debris and to overestimate velocities.

In about 70% of the cases, reasonable simulation of the total runout was produced with the Voellmy model, with the friction coefficient set to a constant 0.1 (bulk friction angle 5.7 degrees) and the turbulence coefficient of 500 m/sec^2.

Good predictions of rock avalanche runout can be produced by case-specific calibration of the model, using prototype events similar to the landslide under investigation.

DAN is also capable of accounting for the variation of the rheological properties along the path and longitudinally within the sliding body. It is also possible to account for gradual entrainment of material from the path. Calibration of these features of the model is in progress.

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