Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publ. no. 209, 1992.

Predicting debris-flow runout and deposition on fans: the importance of the flow hydrograph

KELIN X. WHIPPLE

Department of Geological Sciences, University of Washington, Seattle, Washington 98195, USA

Abstract A simple model of debris-flow deposition on fans is presented. The model couples field studies of debris-flow rheology with simple calculations in order to illustrate, in a general manner, the controls on the patterns of debris-flow deposition on fans. The predictions are insensitive to the form of rheological model (results for Bingham and Newtonian models are presented). The nature of the flow hydrograph, on the other hand, is shown to be of first order importance. Unfortunately, in many geological environments, little is known about the physical controls on the temporal variation in discharge and sediment concentration characteristic of debris-flow hydrographs.

INTRODUCTION

Continuing expansion of population centres into mountainous areas has increased the need for basic research on debris-flow fans. There is a need to understand the construction of debris-flow fans, in order to predict, mitigate, or control the hazard posed by debris flows to communities situated on them (Takahashi, 1981; Costa, 1984). In such an effort one must answer the following questions:

(a) under what conditions are debris flows initiated?
(b) how often do they occur?
(c) what volume of material is likely to be involved?
(d) where will the debris flows overtop channel banks and inundate the fan surface?
(e) what controls the sudden channel avulsions which are characteristic of the fan environment?

Although much has been learned about debris-flow initiation and growth (items (a)-(c)), the controls on the patterns of debris-flow deposition on fans remain poorly understood.

The behaviour of debris flows is known to be sensitive to the physical composition of the slurry, with much variability occurring between debris flows in different geological settings (Takahashi, 1981; Costa, 1984). Partly because of this regional variation, much debate has surrounded the search for the correct form of rheological model for debris flows. Debris flows, however, are a complex phenomenon, commonly exhibiting unsteady, surging flow behaviour and temporal variations in sediment concentration (Okuda *et al.*, 1980; Pierson, 1984; 1986); in addition to a rheological model, predicting debris-flow runout requires an understanding of: (a) the temporal variations in discharge, grain-size distribution (GSD), and sediment concentration (C_s), and (b) the associated temporal variations in rheological parameters.

In this paper no attempt is made to present a thorough analysis of the physical controls on the form of debris-flow hydrographs, nor to present a model designed to supersede existing fan-deposition models (e.g. Mizuyama *et al.*, 1987). Instead an attempt is made to illustrate (a) how field measurements can be used to constrain the parameters for any rheological model, and (b) that the accurate description of the debris-flow hydrograph is far more important to successful prediction of debris-flow depositional patterns than the choice of the rheological model.

DEBRIS-FLOW RHEOLOGY

Background

Debris flows can be modelled as non-Newtonian fluids with finite yield strengths and high viscosities. For the purpose of this study, the visco-plastic, or Bingham, flow law proposed by Johnson (1970) is taken as an adequate description of debris-flow dynamics:

$$\tau_{zx} - \tau_o = \mu_B \frac{\mathrm{d}u}{\mathrm{d}z} \qquad \tau_{zx} > \tau_o \tag{1a}$$

$$\frac{\mathrm{d}u}{\mathrm{d}z} = 0 \qquad \tau_{zx} \leq \tau_o \tag{1b}$$

where (τ_{zx}) is the driving stress, (τ_o) is the yield strength, (μ_B) is the viscosity, and ($\mathrm{d}u/\mathrm{d}z$) is the velocity gradient. Yield strength and viscosity are constrained to be constant for each debris flow or debris-flow surge modeled. Yield strength and viscosity are sensitive to, at least, the physical composition of the slurry, but may also depend on strain-rate or other dynamic factors, here assumed to have negligible effect.

Both yield strength and viscosity increase rapidly with sediment concentration, as documented and quantified in recent laboratory studies (e.g. O'Brien & Julien, 1988). Obtaining such a quantitative understanding of the physical controls on yield strength and viscosity is required before the Bingham model can become a useful predictive tool. Unfortunately, laboratory studies have been unable to reproduce the range of yield strengths and viscosities estimated in the field (Costa, 1984), and thus are not directly applicable to field problems. Therefore, it is necessary to constrain yield strength and viscosity via reconstruction of peak flow hydraulics from well-preserved debris-flow deposits. Naturally, any rheological model can be "calibrated" from field data in this way. For the simple Newtonian model, only the effective viscosity will change as a function of GSD and sediment concentration.

Field and computational methods

Yield strength is estimated from measurements of deposit thickness (h) and surface slope (θ) using the relation ($\tau_o = \gamma h \sin\theta$; where γ is the unit weight of the debris) given by Johnson (1970). The margins of overbank lobes on smooth surfaces are the preferred locations for making these measurements. Suitable locations are not difficult to find and consistent estimates of yield strength are easily obtained.

Flow viscosity is more difficult to constrain. Most published estimates of debris flow viscosities from field data have been based on equations given by Johnson (1970) for flow through channels with approximately circular cross sections. These equations can result in significant errors if applied to channels with cross sections that deviate from the ideal circular geometry. In order to avoid such problems a numerical scheme capable of handling channels of arbitrary cross-sectional form is employed here for back-calculating flow viscosities.

This model solves the equations for steady, rectilinear flow of a Bingham material through a user-specified channel cross section. For a Bingham fluid, the downstream (x-direction) momentum equation reduces to:

$$\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \frac{\gamma \sin\theta}{\mu_B} \qquad [\tau_{zx}^2 + \tau_{yx}^2]^{0.5} > \tau_o \tag{2a}$$

$$\frac{\partial u}{\partial y} = \frac{\partial u}{\partial z} = 0 \qquad [\tau_{zx}^2 + \tau_{yx}^2]^{0.5} \leq \tau_o \tag{2b}$$

where u is the downstream component of the velocity, y is the cross-stream direction, and z is oriented perpendicular to the channel bed. Equation (2a) is identical to the momentum equation for a rectilinear flow of a Newtonian fluid, but is applicable only in the deforming region (where the condition $\tau_{zx} > \tau_o$ holds) and is subject to different boundary conditions. The influence of the yield strength, which does not appear explicitly in equation (2a), is imposed through the correct application of the boundary conditions. The numerical scheme has been tested against the analytical solution for flow through a circular channel (Johnson, 1970) and predicts discharge and plug velocity to within $\pm$ 5% of the analytic values.

Where flow discharges can be estimated from field data, this numerical solution can be used to back-calculate the flow viscosity, provided the yield strength is known. Viscosities estimated in this manner are subject to the errors in the yield strength estimate, the average velocity estimate, and the reconstructed estimate of flow cross-sectional area. Therefore, viscosity estimates are reported as the plausible range allowed by field data. Field measurements necessary to constrain the yield strength and viscosity of debris flows are listed below.

Field example: Black Canyon, California

Two recent debris-flow deposits (dating from 1983 and 1990) on the Black Canyon Fan near Independence, California, were studied. The field methodology included:

(a) mapping of the internal stratigraphy of the deposits to determine the extent and chronological sequence of individual debris-flow surges;
(b) determination of the GSD of the deposits of each surge;
(c) measurement of the thickness and surface slope of overbank deposits of each surge; and
(d) measurement of super-elevation of mudlines, curvature, and cross-sectional geometry at channel bends.

Mapping established a sequence of six distinct surges (I-IV, 1983; and I-II, 1990). All except the first surge of the 1983 flow (83-I) are sufficiently well preserved to allow a detailed reconstruction of flow hydraulics. Inter-surge variability in deposit GSD is minimal. Yield strength estimates were derived from the measurements of deposit thickness and slope. Peak discharge (Q_p) of each surge was estimated from the measurements of flow super-elevation (Δh), flow width (w), and cross-sectional area at bends with well preserved mudlines by applying Chow's formula for steady, uniform radial flow through a bend with radius of curvature (r_c):

$$\langle u \rangle = \left[\frac{\Delta h}{w} r_c g \right]^{0.5} \tag{3a}$$

$$Q_p = \langle u \rangle A \tag{3b}$$

where $\langle u \rangle$ is the cross-sectionally averaged velocity, and A is the cross-sectional area of the flow. Viscosity was back-calculated for each surge from the discharge and yield strength estimates. Estimates of the effective Newtonian viscosity were also obtained for each surge by repeating the viscosity calculation for the case of a zero yield strength.

Estimated values of yield strength, flow velocity, flow cross-sectional area, peak discharge, Bingham viscosity, and Newtonian viscosity are listed in Table 1. These results document a well-defined correlation between yield strength and viscosity which is consistent with a progressive dilution of successive surges of the Black Canyon debris flows - a phenomenon commonly observed in debris flows elsewhere (Pierson, 1984; 1986). The yield strength and viscosity data in Table 1 are therefore interpreted as functions of sediment concentration (Fig. 1). With the rheology thus constrained, some simple calculations can be made to predict the general patterns of debris-flow deposition if the form of the hydrograph is known.

Table 1 Hydraulic and rheological parameters: Black Canyon, California.

Debris-flow surge	Cross-sectional area (m^2)	Average velocity ($m\ s^{-1}$)	Peak discharge ($m^3\ s^{-1}$)	Yield strength (Pa)	Bingham viscosity (Pa s)	Newtonian viscosity (Pa s)
83-II[a]	56	7.8	435±15	2150±150	430±50	1000
83-IIIa[b]	19	5.2	95±15	540±30	380±70	550
83-IIIb[b]	13	6.0	75±12	540±30	180±45	290
83-IV	6	4.8	22±8	300±45	30±15	60
90-I	13	5.2	68±10	340±80	225±75	280
90-II	2	4.5	8±1	80±35	18±3	22

[a] No estimates available for pulse 83-I.

[b] Estimates a and b for pulse 83-III taken at different locations.

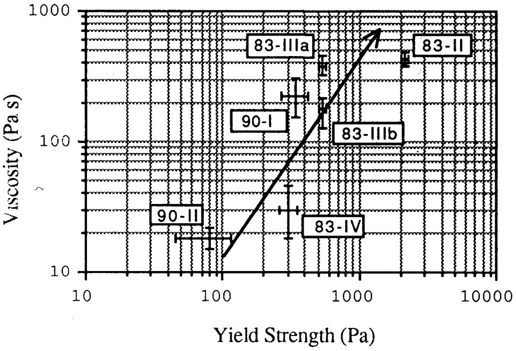

Fig. 1 Rheology of the 1983 and 1990 Black Canyon debris flows. The arrow indicates the inferred trend of yield strength and viscosity with C_s (range *c.* 66-74% solids by volume).

THE DEBRIS-FLOW HYDROGRAPH

A typical debris-flow hydrograph can be drawn from continuous records of the hydraulic characteristics (stage, velocity) and physical properties (i.e. sediment concentration) of debris flows, which are now available from sites in Japan (Okuda *et al.*, 1980) and in the United States (Pierson, 1984; 1986). Such a generalized hydrograph would incorporate at least the surging flow and temporal variation in sediment concentration observed in most debris flows. These features are captured schematically in Fig. 2(a). Figure 2(a) shows both the intra-surge variation in sediment concentration and the gradual inter-surge dilution of the flow. Variations in the GSD of the flow are assumed to be negligible in the present analysis. Although simplified, this generalized hydrograph retains temporal variations which characterize the flow of debris slurries, but which complicate modelling efforts.

For the purpose of the present study, an idealization of the debris-flow hydrograph is proposed (Fig. 2(b)). In this idealized form, debris flows with complex hydrographs are modelled as a series of steady pulses, each governed by constant values of yield strength and viscosity. The yield strength and

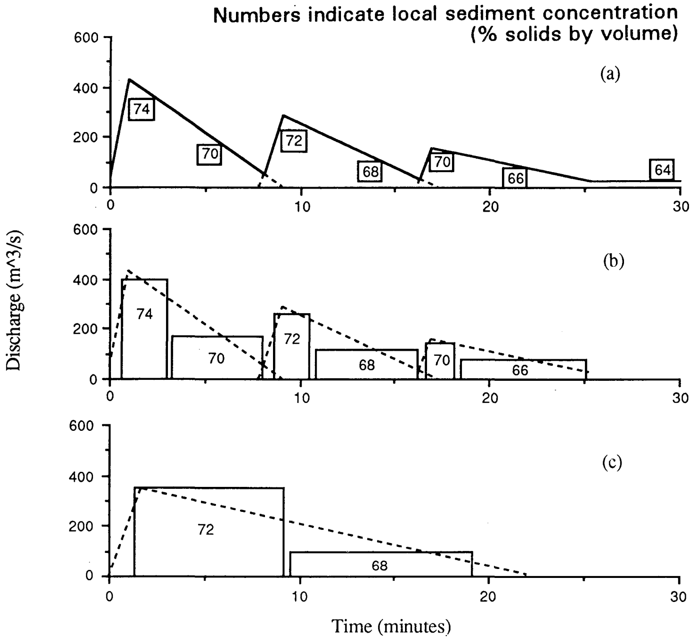

Fig. 2 Schematic debris flow hydrographs: (a) hydrograph generalized from observational data in Pierson (1984); (b) and (c) idealized hydrographs.

viscosity vary between the pulses according to variations in the average sediment concentration (Figs 2(b) and (c)). The alternative hydrograph shown in Fig. 2(c) represents a debris flow similar to that in Fig. 2(b) (total volumes of sediment and water are identical), but without the surging behaviour. Such a difference might arise in nature in debris flows initiated by different mechanisms or under different conditions.

For the purpose of illustration, yield strengths and viscosities (or Newtonian viscosities) are arbitrarily assigned to the sediment concentration values shown in Figs 2(b) and (c). These assignments are guided by the apparent trend of yield strength and viscosity (or Newtonian viscosity) with increasing sediment concentration shown in Fig. 1.

PREDICTION OF DEBRIS-FLOW DEPOSITIONAL PATTERNS

Debris flows commonly follow existing channel courses across fan surfaces. The critical questions involved in efforts to predict debris-flow depositional patterns are:

(a) where will the flow overtop the channel banks?
(b) what area will be inundated? and
(c) will the channel course be diverted by in-channel debris-flow deposition?

At the most fundamental level, channel conveyance capacity must be determined as a function of both position on the fan and flow rheology. A rudimentary flow routing model can be developed using the simple rule that discharge in excess of the conveyance capacity at any position is sent overbank while the remainder continues down fan. This simple routing rule ignores backwater effects and the potential for the self-confinement of the flows between their own levees, but provides a first-order estimate of volume of overbank deposition.

Calculations based on the rheology of the Black Canyon debris flows (Fig. 1), the hypothetical debris-flow hydrographs in Figs 2(b) and (c), and field measurements of channel size and slope as a function of distance from the apex for a fan in Owens Valley, California, can be used to give a quantitative description of the debris-flow conveyance system. Channel conveyance capacity is calculated, using the numerical open-channel flow model, as a function of flow sediment concentration and distance downfan for both the Bingham and Newtonian rheological models (Fig. 3). The conveyance capacities predicted for the two rheologies are nearly identical (Fig. 3 shows results for the Bingham model).

Contrasting the estimated channel capacities in Fig. 3 with the discharge of each of the pulses of our idealized hydrographs allows a prediction of the locus of overbank deposition for each debris flow. The volume of material deposited overbank per kilometre of channel can be estimated as the difference between discharge into and out of each kilometre-long reach of the channel (Fig. 4). This simple calculation demonstrates that:

(a) at least for well-channelized flows, the predicted depositional pattern is not sensitive to the choice of rheological model, and

(b) the depositional pattern is quite sensitive to the shape of the input hydrograph (Fig. 4).

This observation is not limited to the Bingham and Newtonian models: the general pattern of debris-flow deposition could be accurately predicted with any reasonable, adequately constrained rheological model. Thus, although it is advisable to use the rheological model which most fully describes the behaviour of the debris flows in a given field area, accurate prediction of the debris-flow hydrographs is, in fact, of most critical concern for the proper assessment of

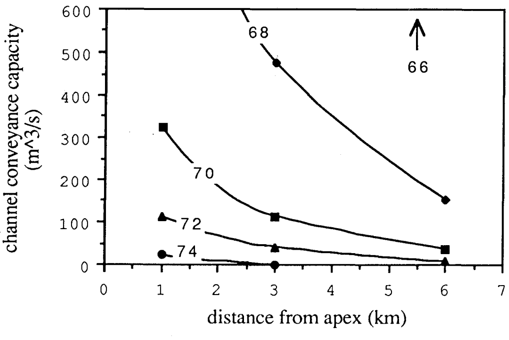

Fig. 3 Conveyance capacity of channels as a function of distance downfan for debris flows with differing sediment concentrations (66-74% solids by volume). Yield strength and viscosity were assigned arbitrarily, based on the inferred trend with C_s in Fig. 1.

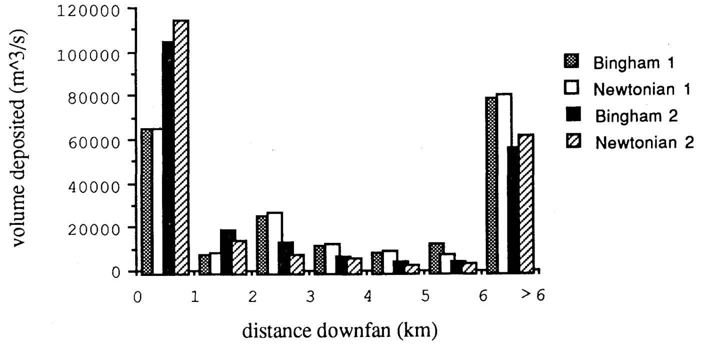

Fig. 4 Volume of material deposited overbank per kilometre length of channel. Calculations for idealized hydrographs 1 and 2 (Fig. 2(b) and (c)) based on Bingham and Newtonian rheologies are compared.

probable zones of debris-flow inundation.

DISCUSSION

The importance of debris-flow hydrographs and the processes which control them has been recognized by previous studies, and is well documented in a study by Fairchild (1987). However, with the exception of some work done in Japan (Takahashi, 1981), there has been, to my knowledge, little work on the physical controls on the temporal variation in sediment concentration in debris flows. In the absence of significant theoretical advances in the understanding of debris-flow hydrodynamics and the temporal evolution of debris-flow hydrographs, we must look to studies of fan deposits and fan morphology to provide insights. Characterization of debris-flow hydrographs could, I believe, be achieved in studies that couple careful rheological analyses of recent debris flows (e.g. Table 1; Fig. 1), mapping of debris-flow depositional patterns, modelling of debris-flow deposition (e.g. Mizuyama *et al.*, 1987), and statistical quantification of the yield strengths and volumes of debris-flow deposits preserved in the fan stratigraphy.

Acknowledgements The research presented here was funded by NSF GRANT # EAR-9004843 to Thomas Dunne. Discussions with D. Miller and D. Mohrig have contributed significantly to my understanding of debris-flow processes. Thoughtful reviews by these colleagues, T. Dunne, and K. MacLeod greatly improved an early version of the manuscript.

REFERENCES

Costa, J. E. (1984) Physical geomorphology of debris flows. In: *Developments and Applications of*

Geomorphology (ed. by J. E. Costa & P. J. Fleisher), 269-315. Springer-Verlag, Berlin.

Johnson, A. M. (1970) *Physical Processes in Geology*. Freeman, Cooper & Co., San Francisco.

Fairchild, L. H. (1987) The importance of lahar initiation processes. In: *Debris Flows/Avalanches: Process, Recognition, and Mitigation* (Geol. Soc. Am. Reviews in Engineering Geology, vol. VII) (ed. by J. E. Costa & G. F. Wieczorek), 51-61.

Mizuyama, T., Yazawa, A. & Ido, K. (1987) Computer simulation of debris flow depositional processes. In: *Erosion and Sedimentation in the Pacific Rim* (ed. by R.L. Beschta *et al.*) (Proc. Corvallis Symp., August 1987), 179-190. IAHS Publ. no. 165.

O'Brien, J. S. & Julien, P. Y. (1988) Laboratory analysis of mudflow properties. *J. Hydraul. Engng* **114**, 877-887.

Okuda, S., Suwa, H., Okunishi, K., Yokoyama, K. & Nakano, M. (1980) Observations on the motion of a debris flow and its geomorphological effects. *Z. Geomorphol.*, Suppl. Bd **35**, 142-163.

Pierson, T. C. (1984) Effects of slurry composition on debris flow dynamics, Rudd Canyon, Utah. In: *Delineation of Landslide, Flash Flood, and Debris Flow Hazards in Utah* (ed. by D. S. Bowles) (Proc. Spec. Conf., Logan, Utah, USA), 132-152.

Pierson, T. C. (1986) Flow behavior of channelized debris flows, Mount St. Helens, Washington. In: *Hillslope Processes* (ed. by A. D. Abrahams), 269-296. Allen & Unwin, Boston.

Takahashi, T. (1981) Debris flow. *Ann. Rev. Fluid Mech.* **13**, 57-77.