Springer
Berlin
Heidelberg
New York
Barcelona
Budapest
Hong Kong
London
Milan
Santa Clara
Singapore
Paris
Tokyo

Aronne Armanini
Masanori Michiue (Eds.)

Recent Developments on Debris Flows

Springer

Chapter 2

Dynamics of Debris Flow

Introduction

Pierre Julien

It is a privilege to introduce the reader to four papers on debris flows and hyperconcentrations of sediment. The purpose of this brief report is to guide the reader and to outline the most relevant aspects of the recent scientific contributions to the field of debris flow dynamics. This set of papers nicely contributes to recent developments in terms of rheology, laboratory experiments, and field verification of numerical models for the simulation of mud flows and debris flows. It is interesting to note that the dynamics of debris flows can only be captured through clear understanding of the rheology of hyperconcentrations of sediments. The reader must overcome complexities inherent to different nomenclatures and the tendency for each author to present different rheological models. This set of papers presents a complete description of the various shear stress components due to the bonding between cohesive particles, fluid viscosity including viscous interactions with sediment particles, turbulence, and dispersive stress due to inertial collisions between particles. Jan and Shen clearly present an unprejudiced review of several models with primary results summarized in five tables.

Recent advances in rheology include quadratic formulations of shear stress. The quadratic shear stress equation of O'Brien and Julien (1985) combines yield strength, viscosity, turbulence, and dispersive stress. Equivalent quadratic shear stress relationships are also found in Takahashi, and Jan and Shen. Julien and O'Brien show numerical solutions after the friction slope is subdivided into three components; the yield slope, the viscous slope and the turbulent-dispersive slope. The approach is quite simple compared to the untractable analytical solutions for velocity and sediment concentration profiles. The quadratic model includes the inertial formulation of Bagnold's dispersive stress for which experimental data has been collected in recent years for comparison with the original experiments. There is growing evidence that the dispersive stress concept is not as simple as initially pictured by Bagnold:

a) Takahashi clearly demonstrates in his Figure 2 that the coefficient f of Bagnold's equation varies by at least an order of magnitude when compared with the experiments of Daido et al. (1984) and Campbell and Brennen (1985). Commemorating the 40th anniversary of Bagnold's contribution, the reader would have expected the empirical calibration coefficient to be known with two significant digits. The large scatter in Figures 2 and 5 is rather unconvincing, considering that several laboratory experiments were deliberately carried out under conditions similar to Bagnold's original study.

b) The use of neutrally buoyant material ($\sigma = \rho$) also poses mathematical difficulties of the type $0 \neq 0$ in Equations 21 and 27 when the granular material is under deformation $du/dz \neq 0$.

The laboratory measurements of velocity profiles by Takahashi in the inertial regime (Figure 6), and by Hashimoto for dry sand (Figure 6) and sand-water mixtures (Figure 12) are particularly enlightening:

a) In all cases, the reader will notice that the velocity increases almost linearly with depth. The similarities with the model of Duboys (1879) cannot be overlooked. This has a considerable practical meaning in that despite the diverse velocity profiles suggested in the literature, the practitioner can simply use the linear velocity profile as a first approximation. Accordingly, the surface velocity is approximately twice the mean debris flow velocity. The reader should compare the velocity profiles suggested by Jan and Shen (in Tables I-V) with the observations of Hashimoto (Figures 6 and 12) and Takahashi (Figure 6). The main reason for the discrepancies is that the suggested velocity profiles are calculated assuming a uniform sediment concentration. In reality, the increased near-bed sediment concentration reduces the velocity in the lower part of the velocity profile.

b) The reader should pay attention to the average rate of deformation in velocity profiles. For instance, in Takahashi's Figure 6, $du/dz \cong 10/s$, which is very small compared to the deformation rates required for inertial particle impact in Bagnold's experiments ($50 < du/dz < 300$). Considering near-linear velocity profiles, the practitioner will notice that given a typical flow depth of 2m and surface velocity of 20m/s, the average rate of deformation in natural debris flows is very small, i.e. $du/dz = 10/s$.

Progress has also been made in the analysis of both average and surface velocities. Hashimoto presents relationships for surface velocity u_s/u_* and mean velocity $\overline{u}/u_*$ proportional to h/d as shown in Eqs. 19, 20 and 27 where $\overline{u}$ is the mean velocity, u_s is the surface velocity, u_* is the shear velocity, h is the flow depth and d is the grain diameter. This analysis is quite intriguing, because given the grain size and shear velocity, not only the velocity profile but also the mean flow velocity increases linearly with flow depth. This linear model is in agreement with laboratory data at values of $h/d < 30$ has shown on Figures 7 and 13 of Hashimoto's paper. However, the experimental data deviates substantially from the inertial model of Hashimoto at values of $h/d > 30$. When $h/d > 30$, the reader may find better agreement with a turbulence equation of the type:

$\frac{\overline{u}}{u_*} = 5.75 \log \alpha \frac{h}{d}$, in which a value $\alpha = 1$ (compared to $\alpha = 12.2$ for clear water) fits the experimental observations of Hashimoto on both Figures 8 and 13, and to some extent in Figure 7, considering $u_s \cong 2\overline{u}$. In any event, the practitioner will notice that the mean debris flow velocity is less than that calculated with traditional turbulent flow equation ($\alpha = 12.2$).

One of the primary conclusions of this set of papers is that the inertial impact of particles cannot be dominant when $h/d > 30$. Hashimoto's conclusion also finds support in Takahashi's paper stating that the turbulent flow regime in natural sand and water mixtures appears when $h/d > 20$–30, with reference to Arai and Takahashi (1986). This important conclusion is very practical in that for debris flows where typical flow depths reach 2m, a particle size of at least 80mm is required to induce sufficient dispersive stress to overcome the turbulent stress. Consequently, natural debris flows of particle mixtures finer that 80mm (gravel, sand, silt and clay) remain either turbulent or viscous, but not dispersive.

In summary, significant progress has been made in recent years in understanding the dynamics of debris flows. Most shear stress components have been identified and several components can be estimated from available laboratory experiments. The quadratic rheological model seems effective; the quantitative evaluation of all components describing yield, viscous, turbulent and dispersive stresses is readily possible, although subject to refinement. Advances in the analysis of velocity profiles, surface and mean flow velocities lead to the conclusion that particle impact cannot be dominant when $h/d > 25$. The practitioner will find that velocity profiles are nearly linear and the rates of deformation are very small, of the order of $du/dz \cong 10/s$. The mean flow velocity is less than calculated with the standard turbulent flow equation with $\alpha = 12.2$.

Future improvements are possible through an accurate determination of: 1) viscosity as a function of the concentration of fine particles; 2) mixing length generating turbulent stress in hyperconcentrations; and 3) the coefficient f of the dispersive stress relationship. Experimental research on inertial impact of coarse gravel particles, naturally non-buoyant particles is in dire need. A better understanding of the effects of clay mineralogy and fine sediment concentration on the viscosity of a mixture will improve our understanding of the rheology of hyperconcentrations. Advances in our physical understanding of the dynamics of debris flows will enhance our ability to model hyperconcentrated flows, mud flows, and debris flows. These simulation models will in turn facilitate improved design of adequate countermeasures to protect living communities against devastating debris flows.

Selected Notes on Debris Flow Dynamics

P.Y. Julien[1] and J.S. O'Brien[2]

[1] Engineering Research Center, Colorado State University, Fort Collins, CO 80523, USA

[2] Hydraulic Engineer, FLO Engineering, Inc. P.O. Box 1659, Breckenridge, CO 80424, USA.

Abstract

Heavily sediment-laden flows have been described and classified as hyperconcentrated sediment flows, including mud floods, mudflows, and debris flows. The authors prescribe definitions based on governing physical processes and limited concentrations of cohesive material. Viscous mudflows contain large concentrations of fine cohesive material. Rocky debris flows contain large concentrations of clastic material. Rheological analyses should recognize four types of shear stresses: 1) yield stress; 2) viscous stress; 3) turbulent stress; and 4) dispersive stress. These shear stresses combine into a quadratic rheological model. Dimensionless parameters from the ratio of shear stress terms identify the predominant physical process.

The two-dimensional model FLO-2D has been developed for the simulation of a wide range of hyperconcentrated sediment flows based on the quadratic rheological model. The simulation of the Pine Creek mudflow during the 1980 eruption of Mount St. Helens is presented as an example of our continuing progress in the physically-based analysis of natural disasters from heavily sediment-laden flows.

1. Introduction

The general classification of heavily sediment-laden flows describes various types of hyperconcentrated flows. Hyperconcentrated sediment flows ranging from water floods to debris flows are initiated with intense rainfall or snowmelt and may be triggered by hillslope and bank failures as well as landslides. Earthquakes and volcanic activities may also initiate the process of massive mobilization of liquefied soils in steep channels which may then

deposit on alluvial fans. The flow properties and runout distances of these flow events are governed by the volume of the fluid matrix and the sediment properties.

Hyperconcentrations of non-cohesive particles with limited quantities of cohesive sediment display fluid characteristics at volumetric sediment concentrations $15\% < C_v < 40\%$ and are referred to as mud floods. Mud floods are turbulent and resistance to flow depends on boundary roughness. The sediment concentration tends to become fairly uniform throughout the flow depth because the increased fluid viscosity reduces the settling velocity of sediment particles. Woo et al. (1988) provided a detailed analysis of hyperconcentrations of sands.

In mudflows, the concentration of silts and clays is sufficiently high to bond the fluid matrix and to support clastic material. Mudflows behave as a singular fluid mass where boulders may be rafted along the surface. The fluid matrix has a relatively large concentration of sediments finer than 0.0625 mm and water. The volumetric sediment concentration of such fluid matrix roughly ranges from 45 – 55% depending on the relative proportion of silts and clays. Mudflows exhibit high viscosity and high yield stress, can travel long distances on mild slopes at slow velocities and leave lobate deposits on alluvial fans. The flow is primarily laminar and local turbulence is quickly dampened. A detailed rheological analysis of mudflow properties has been presented by O'Brien and Julien (1988).

The analysis of debris flows stems largely from the contributions of Bagnold (1954) and Takahashi (1978). We suggest that debris flows represent a water-sediment mixture that contains significant quantities of boulders and debris where inter-particle impact is the dominant mechanism for energy dissipation. Debris-laden fronts may slow the progress of the flow or divert it in another direction. Particle interaction of sediment clasts can be a significant mechanism to transfer momentum to the flow boundary. Granular flows constitute a sub-class of debris flows in which the exchange of momentum between the flow core and the boundary occurs almost exclusively through particle collision. The water, which may be present in small quantities does not influence particle collision or lubricate the mass. Our understanding of sediment particle interaction in flowing water evolved from the study of O'Brien and Julien (1985). The definitions involving hyperconcentrated sediment flows should focus on the physical processes of the fluid motion which can be explored through the rheological study of sediment hyperconcentrations. Nomenclature has been formulated on the basis of what constitutes the fluid matrix (mixture of water and fine sediment particles) which govern the flow properties.

2. Rheology of Hyperconcentrated Sediment Flows

The non-Newtonian nature of hyperconcentrations results from several physical processes: The cohesion and bonding of fine sediment particles τ_c; the Mohr-Coulomb shear τ_{mc}, which is important when considering the static stability of steep slopes; the yield stress τ_y is defined as the sum of cohesive strength τ_c, plus the Mohr-Coulomb shear τ_{mc} and must be exceeded to initiate motion; the viscous shear stress τ_v which accounts for the increase in Newtonian viscosity; the turbulent shear stress τ_t which describes the turbulent nature of hyperconcentrated sediment flows of fine granular material; finally, the dispersive stress τ_d describes the effects of the collision of sediment clasts. Energy dissipation through turbulence, large eddies trailing major obstacles like trees and boulders, can be accounted for by considering τ_t.

The total shear stress τ in hyperconcentrated sediment flows includes contributions from each of these five shear stress components:

$$\tau = \tau_{mc} + \tau_c + \tau_v + \tau_t + \tau_d \tag{1}$$

When written in terms of shear rates, or velocity gradient $\left(\frac{du}{dy}\right)$, the following quadratic rheological model is obtained:

$$\tau = \tau_y + \eta \frac{du}{dy} + \zeta \left(\frac{du}{dy}\right)^2 \tag{2}$$

where

$$\tau_y = \tau_{mc} + \tau_c$$

$$\zeta = \rho_m l_m^2 + a_i \rho_s \lambda^2 d_s^2$$

In the above equations η is the dynamic viscosity of the mixture; τ_c is the cohesive yield strength; and τ_{mc} is the Mohr-Coulomb shear stress $\tau_{mc} = p_s$ tan ϕ depending on the intergranular pressure p_s and the angle of repose ϕ of the material; ζ is the inertial shear stress coefficient depending on the mass density of the mixture ρ_m, the Prandtl mixing length l_m, the sediment size d_s, the volumetric sediment concentration C_v, and ρ_s is the mass density of sediment. The mixing length l_m is usually given as a function of the distance from the boundary y and the von Karman constant κ . As a first approximation in depth-integrated flows, one can use the flow depth h, and a constant $\kappa = 0.4$ and the approximate mixing length is given by $l_m \cong 0.4h$. The coefficient a_i has been shown to vary widely and Takahashi proposed $a_i \cong 0.01$. Bagnold defined the linear sediment concentration λ as

$$\frac{1}{\lambda} = \left(\frac{C_m}{C_v}\right)^{1/3} - 1 \tag{3}$$

in which the maximum concentration of sediment particles $C_m \cong 0.615$. It is important to consider that the occurrence of debris flows as prescribed by a dispersive stress relationship alone requires that the following three conditions be simultaneously satisfied: 1) very large sediment concentrations, typically exceeding $C_v > 0.5$; 2) large velocity gradients typically exceeding $10s^-1$; and 3) very large grain sizes typically coarser than gravel in nature.

From equation 2, Julien and Lan (1991) proposed a dimensionless formulation of the quadratic rheological model in the form:

$$\tau^* = 1 + (1 + T_d^*)\ a_i D_v^* \tag{4}$$

in which the three dimensionless parameters $\tau*, D_v^*$ and T_d^* are defined as:

1. dimensionless excess shear stress τ^*

$$\tau^* = \frac{\tau - \tau_y}{\eta \frac{du}{dy}}$$

2. dimensionless dispersive-viscous ratio D_v^*

$$D_v^* = \frac{\rho_s \lambda^2 d_s^2}{\eta} \left(\frac{du}{dy} \right)$$

3. dimensionless turbulent-dispersive ratio T_d^*

$$T_d^* = \frac{\rho_m l_m^2}{a_i \rho_s \lambda^2 d_s^2}$$

It is suggested to relate the following parametric delineations to the classification of hyperconcentrations: 1) mudflows when yield and viscous stresses are dominant at $D_v^* < 30$; 2) debris flows or granular flows for which the dispersive stress is dominant at $D_v^* > 400$ and $T_d^* < 1$; and 3) mud floods when the turbulent shear stress is dominant at $D_v^* > 400$ and $T_d^* > 1$. A transition regime may be expected when $30 < D_v^* < 400$ for which all the terms of the quadratic equation are not negligible.

3. Two-Dimensional Simulation Model Flo-2d

Based on the quadratic rheological model, O'Brien et al. (1993) developed the two-dimensional flow routing model FLO-2D for the simulation of the continuum from water floods to mudflows. The momentum equation is solved after considering three components of the total friction slope S_f, namely: the yield slope Sy, the viscous slope S_v, and the turbulent-dispersive slope S_{td}. The total friction slope can therefore be rewritten as:

$$S_f = \frac{\tau_y}{\gamma_m h} + \frac{K \eta V}{8 \gamma_m h^2} + \frac{n^2 V^2}{h^{4/3}} \tag{5}$$

in which γ_m is the specific weight of a mixture, h is the flow depth, V is the depth-averaged flow velocity, $K = 24$ for wide-rectangular channels but increases with roughness and irregular cross-section geometry, and n is Manning equivalent roughness coefficient for the turbulent-dispersive stress. The yield stress τ_y and the dynamic viscosity η increase with sediment concentration as defined by O'Brien and Julien (1988). The details pertaining to the model FLO-2D are available in O'Brien et al. (1993). Numerous mudflow hazard delineation projects have been completed using the FLO-2D model.

4. Mudflow Simulation of Pine Creek Using Flo-2D

In 1980, Mount St. Helens erupted, creating an explosive charge of gas, mud and water that cascaded as a pyroclastic surge down the cone of the volcano before collapsing into a high velocity mudflow or lahar down several drainages on the mountainside such as the Pine Creek channel sketched on Figure 1 (after Pierson, 1985). The data base of the Pine Creek mudflow was sufficiently complete to replicate the historic mudflow event. The mudflow traveled 22.5 km in 20 ± 3 minutes before entering Swift Reservoir where the mudflow volume and the peak discharge was estimated by response of a stage recorder at Swift Dam (Pierson, 1985).

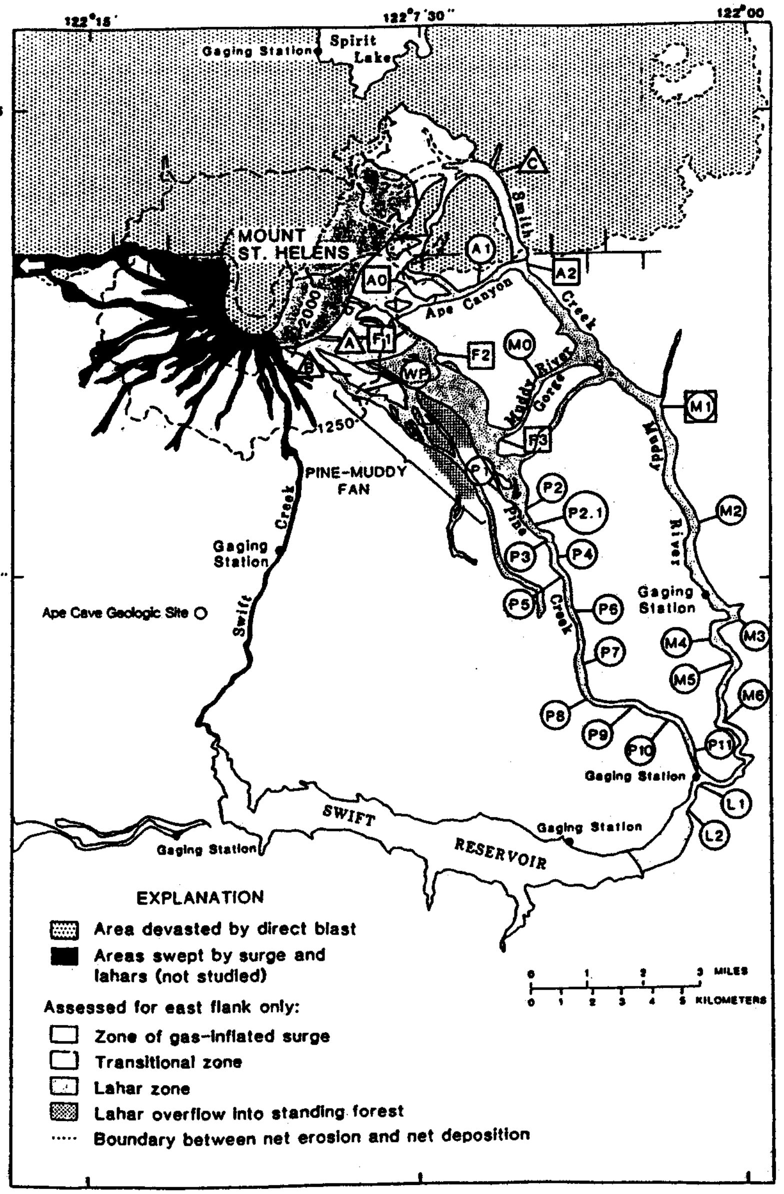

Fig. 1. Location of Pine Creek near Mount St. Helens (form Pierson, 1985; reproduced with permission of the Geol. Soc. of America)

It was necessary to estimate the initial flood hydrograph at the first cross-section to reproduce the volume of mudflow entering Swift Reservoir. The USGS provided cross-sections of Pine Creek surveyed after the event. It was reported that only minor amounts of overbank deposition and channel storage took place along Pine Creek.

The simulation of the Pine Creek mudflow was accomplished as follows:

1. a 15 minute topographic map was digitized and a uniform grid system of 500 ft square elements was established over the channel and potential flow areas;
2. a CAD program with a digital terrain model was used to export the grid element coordinates and elevations to a FLO-2D file;
3. rheological parameters for the mudflow were selected from Major and Pierson (1992) assuming a silt-clay to sand ratio of 1:1 for the Mount St. Helens mudflow. The viscosity and yield stress relationships as a function of volumetric sediment concentration were input parameters as a power regression;
4. the channel geometry data for 12 cross-sections were reduced and prepared in a data input file. Selected Manning n values ranged from 0.03 to 0.1. The distances between cross-sections for the FLO-2D simulation were approximated from the mapping provided by the USGS; and
5. the inflow hydrograph was estimated at the first cross-section to reproduce the estimated peak discharge at cross-section 2 and the inflow volume to the reservoir. The first grid element was located several thousand feet upstream of the first cross-section.

The computed mudflow viscosity and yield stress from Major and Pierson (1992) revealed that the equivalent sediment concentration ranged from 60 – 65%. FLO-2D was run several times to replicate the known flow conditions:

1. an estimated peak discharge at cross-section 2 equal to 28,600 $\frac{m^3}{s}$;
2. an estimated peak discharge at the reservoir of 7,500 $\frac{m^3}{s}$;
3. timing of the peak discharge arrival at the reservoir; and
4. estimated volumetric inflow to the reservoir.

When these conditions were satisfactorily met, the computed flow parameters were compared with those estimated by Pierson (1985) at 12 cross-sections. During the Pine Creek FLO-2D simulations, it was noted that an increase of 2% in sediment concentration would result in flow cessation on the falling limb of the hydrograph. This model response assisted in defining the limits in sediment concentration. There was still a question, however, whether the mudflow rheologic parameters used in the FLO-2D simulation would result in high velocity estimates for Pine Creek and would replicate the Swift Reservoir inflow hydrograph. The following FLO-2D results were obtained:

Hydrograph Timing - Arrival of the Peak discharge in Swift Reservoir
Pierson estimate: 20 ± 3 min. FLO-2D simulated: 20.4 min.
Volume - Total inflow volume into Swift Reservoir
Pierson estimate: 13,431,000 m^3 FLO-2D simulated: 13,490,000 m^3
Peak discharge - Peak discharge into Swift Reservoir
Pierson estimate: 7,500 m^3 FLO-2D simulated: 11,750 m^3

The hydrograph timing and volume from the FLO-2D simulations were the most accurate of the three flow conditions based on the response of the Swift Reservoir recording gage. The reservoir inflow peak discharge should be verified by reservoir routing and may be underestimated if the reservoir is shallow and floodwave attenuation was not accurately estimated in predicting the peak flow discharge.

Predicted peak flow velocity and depths correlated well with the estimated flow hydraulics from field data and the estimated values reported by Pierson (Table 1).

Table 1. Comparison of estimated and FLO-2D predicted flow hydraulics in Pine Creek

Xsection	Peak Disch. (m^3/s)		Max. Vel. (m/s)		Max. Flow Dep. (m)	
Grid	Pierson [1]	FLO-2D	Pierson	FLO-2D	Pierson	FLO-2D
P1-1166	17,100	28,300	23.5	21.1	9.8	20.6
P2-1043	28,600	27,200	17.7	20.9	15.2	19.2
P2.1-1009	25,900	27,000	20.8	21.8	12.6	14.0
P3-942	28,200	26,200	13.1	15.6	14.5	16.3
P4-915	21,700	25,000	12.4	19.4	14.9	18.2
P5-856	19,900	24,200	10.9	15.8	14.8	18.7
P6-672	21,000	21,700	14.2	14.0	13.9	20.2
P7-571	19,200	19,200	21.1	12.8	10.7	19.4
P8-432	16,600	18,000	15.3	12.7	9.4	13.0
P9-415	6,250	13,500	9.3	11.7	9.3	19.9
P10-372	8,930	12,500	11.0	9.6	9.0	14.6
P11-196	7,320	12,000	12.0	20.9	6.0	6.4

[1] Table 1 Average Flow Hydraulics from Pierson, GSA Bulletin, 1985, Vol. 96, p. 1064

The following considerations may explain some of the discrepancies. The flow depth was estimated from interpreted mudlines in the channel overbank areas and flow surging, cross-waves, variable cross-section geometry were assumed negligible in estimating the flow depth. It is likely therefore, that the flow depth was overestimated. The flow velocity was estimated by Pierson (1985) on the basis of the flow depth in the channel bends and a superelevation equation from which a peak discharge was computed. It follows that the velocity would be overestimated if the depth is overestimated. It should also be noted that the FLO-2D predicted maximum velocities and flow depths at a given cross-section do not necessarily occur at the same instant.

5. Conclusions

The rheology of hyperconcentrations is relatively complex, but the quadratic formulation appropriately describes the continuum of flow conditions ranging from mud floods to debris flows. The quadratic rheological model enables adequate two-dimensional computer simulations of yield, viscous, turbulent and dispersive stress in hyperconcentrated sediment mixtures.

FLO-2D is a flood routing model designed to simulate the continuum of water floods and mudflows in steep channels, over alluvial fans, and on urban floodplains. The Pine Creek mudflow triggered by the eruption of Mount St. Helens was properly simulated with the FLO-2D model. The relatively good correlation of the simulated results with estimated flow characteristics demonstrates the applicability of the model at volumetric sediment concentrations exceeding 60%. The analysis stresses the importance of appropriate values of rheologic parameters such as the dynamic viscosity and yield strength.

REFERENCES

Bagnold, R.A., 1954. Experiments on a Gravity-free Dispersion of Large Solid Spheres in a Newtonian Fluid under Shear, Proc. Royal Soc. of London, Ser. A, 225, 49-63.

Julien, P.Y. and Y.Q. Lan, 1991. On the Rheology of Hyperconcentrations, J. Hyd. Eng., ASCE, 117(3), 346-353.

Major, J.M. and T.C. Pierson, 1992. Debris Flow Rheology: Experimental Analysis of Fine-grained Slurries, Water Res. Res. 28(3), 841-857.

O'Brien, J.S., and P.Y. Julien, 1985. Physical Properties and Mechanics of Hyperconcentrated Sediment Flows, Proc. ASCE Hyd. Div. Spec. Conf on Delineation of Landslides, Flash Flood and Debris Flow Hazards, Logan Utah, June 1984, 260-279.

O'Brien, J.S., and P.Y. Julien, 1988. Laboratory Analysis of Mudflow Properties, J. Hyd. Eng., ASCE, 114(8), 877-887.

O'Brien, J.S., P.Y. Julien and W.T. Fullerton, 1993. Two-dimensional Water Flood and Mudflow Simulation, J. Hyd. Eng., ASCE, 119(2), 244-261.

Pierson, T.C., 1985. Initiation and Flow Behavior of the 1980 Pine Creek and Muddy River Lahars, Mount St. Helens, Washington, Geol. Soc. of America, Bull. V. 96, 1056-1069.

Takahashi, T., 1978. Mechanical Characteristics of Debris Flow, J. Hyd. Div., ASCE, 104, 1153-1169.

Woo, H.S., P.Y. Julien, and E.V. Richardson, 1988. Suspension of large concentrations of sands, J. Hyd. Eng., ASCE, 114(8), 888-898.

DISCUSSION

Armanini: 1. What is the role of roughness in debris flow? 2. What is the difference between debris flow, mudflow and mud flood?

Julien: 1. The question is interpreted to relate to channel boundary roughness, as opposed to surface roughness of individual grains and/or clasts. The influence of channel boundary roughness depends on the flow properties. By analogy with clear water flows, resistance to flow increases with boundary roughness in hydraulically rough turbulent flows but remains insignificant in either laminar flows or hydraulically smooth turbulent flows. Surface roughness should be dominant for turbulent mud floods. Resistance to flow in viscous mudflows depends primarily on fluid viscosity and surface roughness resistance should be small in mudflows. In more viscous flows, or in transition flows, some momentum may be transferred in bends and other flow direction changes such as flow around obstacles. Momentum flux of this nature may be attributed to roughness. 2. We attempted to quantify the relationship between these flow phenomena in previous writings (O'Brien and Julien, 1985). The nomenclature for debris flows is likely to remain muddled as long as the criteria for delineating debris flows, mudflows and mud floods are not quantitatively determined. We contend that better understanding can only be achieved through a rheological analysis of the fluid matrix. This is a complex problem in itself because fluid properties depend on sediment concentration and particle size distribution. The understanding gained from the quadratic rheological model in equation 2 of the paper is that the relative magnitude of the various shear stress components determines the flow type. The nomenclature should therefore depend on the relative magnitude of yield, viscous, turbulent and dispersive stresses. To specifically answer the question, debris flows characterize the motion of coarse granular material with particle impact generating dispersive stress without significant fluid shear stresses. In debris flows, particle impact is dominant everywhere, impact with boundary roughness elements is only part of the total resistance. Mudflows are very viscous to the extent that the entire flow is essentially laminar, resistance to flow depends on fluid properties as opposed to boundary roughness elements. Mud floods are turbulent and resistance to flow depends largely of surface roughness. In the case of mud floods, three types of roughness should be considered: 1) grain roughness over a plane surface; 2) roughness from large elements protruding into the flow such as bridge piers, and large obstructions including buildings and man-made structures; and 3) channel irregularities, sinuosity and changes in channel geometry. In summary, channel resistance should be dominant for mud floods, variable in debris flows and very small in mudflows.

Taniguchi: I find your paper interesting. You said that the volumetric concentration of a mudflow was between 45% and 55%. It think it is too high, and the speed of actual mudflows with such concentration is very slow from the results of my experiments. What do you think?

Julien: The classification in the 1984 paper only provides guidelines or approximate ranges of sediment concentrations expected for different types of hyperconcentrated flows from our field samples. With the work of O'Brien and Julien (1988), it became clearer that any classification based on sediment concentration alone is misleading. the concentration of fines (silts and clays) is most important to determine the yield stress and the viscosity of hyperconcentrations. For instance, it is possible to observe viscous laminar mudflows in laboratory flumes at volumetric sediment concentrations below 20%, but this requires the sediment to contain a larger proportion of clays than usually found in the field. Natural volumetric sediment concentration required for mudflows where the viscous stress largely overcomes turbulent and dispersive stresses usually corresponds to 45-55%. This question highlights the importance of carrying out rheological analyses based on samples representative of field conditions. It is relatively easy in the laboratory to repeat the rheological measurements under various sediment concentrations by controlling the amount of water mixed with the dried in-situ sample. It should be remembered, however, that even landslides, with volumetric concentrations exceeding 65%, can attain extreme velocities on steep slopes, provided that the content of fine sediment is very small.

Kitamura: Concerning the slope failure which you showed on the second slide: 1. Could you show the soil profile of the slope failure site? 2. What are the main factors to cause the slope failure?

Julien: 1. This particular field site showed shallow glacial soils on rough rock outcrops consisting of relatively friable sandstone. The material crumbles from the frequent freeze-thaw cycles during winter and early spring. 2. Slopes are inherently steep but stable when dry. Their stability depends primarily on the moisture content provided by rainstorms and snowmelt. The south-facing slope is subjected to rapid late-spring snowmelt that triggers slope failure. Field reconnaissance surveys should consider the amount of material readily available for transport in steep mountain gullies and available on watershed slopes. Instability indicators include tension cracks, steep loose material, bank caving, and poor vegetation.

Michiue: According to your explanation, in the quadratic terms of shear stress, the turbulent shear stress is dominant in the usual case of debris flow in comparison with the dispersive stress. But I think that the Prandtl mixing length will be influenced by the sediment concentration. It seems to be very difficult to distinguish these to components. What is your opinion on this point?

Julien: We refer to debris flows when the shear stress is dominated by particle impact, which besides dry avalanches and rock falls does not represent all types of hyperconcentrations. Mud floods on the other hand, exert shear stress primarily through turbulence. The question regarding the influence of sediment concentration on the mixing length is truly intriguing among academicians. Traditional understanding promoted by Vanoni, Ippen, and Chien among others showed that the mixing length $l_m = ky$ decreased with sediment concentration because k decreased to $k \cong 0.2$ at large concentrations from the clear water value $k = 0.4$. Coleman (IAHR, JHR, 19,2,1981) challenged this view by introducing a wake flow function while the von Karman constant remains at $k = 0.4$. Woo et al. (ASCE, JHE, 114,8,1988) combined viscous and turbulent stresses for detailed calculations of sediment concentration profiles. It remains unclear as to whether the mixing length varies or not with sediment concentration. In any event, a two-fold change in k from 0.4 to 0.2 is very small compared to the thousand-fold variability of yield and viscous stresses in hyperconcentrations. It can be assumed as a first approximation that $k = 0.4$ for all practical applications to hyperconcentrations and debris flow.

Aguirre Pe: The mixing length $l_m$in $\zeta = \rho_m l_m^2 + a_i \rho^2 d_s^2$ and in $T_d^* = \rho_m l_m^2 / (a_i \rho_s \lambda^2 d_s^2)$ is very important to classify the type of flow and therefore to use the appropriate friction slope in calculations of debris flow. Could you give us some insight about how to determine the mixing length?

Julien: This a very important practical question. As per the response to the previous question, the issue awaits theoretical developments. Until significant research suggests otherwise, there is little evidence that the von Karman varies by more than a factor of 2, which is small compared to the uncertainty in evaluating the viscosity and yield strength of debris flows. For this reason, simple calculations based on $k = 0.4$ are recommended for all calculations. This value is sufficiently accurate at low concentrations. At high concentrations, the other terms of the quadratic equation are usually larger than the turbulent stress.

Takahashi: 1. How did you divide the matrix and the coarse materials in the natural samples? 2. In your simulation of mudflow deposition, what was the condition to stop the flow? I suppose you needed the strength value for the whole materials including coarse materials. 3. Can you sustain particles in suspension with viscous stress only?

Julien: 1. The fluid matrix contains all particle sizes finer than 0.0625 mm. The concentration of silts and clays ($d_m < 0.0625$ mm) defines the sediment concentration of the fluid matrix which is used to determine the yield stress and the viscosity of the hyperconcentration. 2. The condition that stops the flow is determined by the yield stress including the Mohr-Coulomb strength. Only the fine fractions (fluid matrix) determine this strength for mudflows. In the case of debris flows without fines (silt and clay), flow stoppage would be determined by the Mohr-Coulomb criterion only. 3. In mudflows, yield strength alone is sufficient to maintain small particles in suspension without settling if the grain size is smaller than:

$$d_{sb} = \frac{3\pi}{2} \frac{\tau_y}{\lambda_s - \lambda_m}$$

where τ_y is the yield strength, λ_s is the specific weight of sediment and λ_m is the specific weight of the mixture. Very coarse clastic particles settle in mudflows at a velocity which is largely reduced because of the large viscosity of the water-sediment

mixture. The pressure gradient at the wavefront also contributes to move large boulders in the downstream direction. In turbulent mud floods, sand particles can be maintained in suspension by turbulence alone. In summary, at low concentrations, turbulence sustains particles in suspension. As sediment concentration increases, the yield stress also contributes to maintain suspension.

Davies: 1. What are the design criteria for debris flow/mudflow/mud flood protection structures: a) How do you select the size of the structure? b) What procedures do you have to cope with the super-design event when it happens? 2. You showed a slide of a mudflow with a dense bouldery front, and stated that the coarse grains were not important to the phenomenon. This is clearly nonsense, because if you remove the boulders the phenomenon changes fundamentally.

Julien: 1. a) Debris flows generally involve large inertial impact forces with clastic material. It is usually advisable to build sabo dams with thick concrete-walled structures along with ways to drain the interstitial fluid. Without fluid, debris flows rapidly come to a halt. Mudflows are quite different in that the velocities are slow, depths are large and volumes are relatively limited. It is often rewarding to guide mudflows to predetermined storage areas where oozing mudflows can come to a halt. The deposit areas can thereafter be excavated by machinery and the storage capacity replenished after each event. Mud floods must be treated nearly like regular turbulent flows. Effective methods include reducing boundary roughness by channel straightening, obstruction removal and channel lining. Containment berms can be built on floodways to induce sediment storage on the floodplain. For detailed structural design, the flow depth, velocity and impact forces at specific locations can be calculated with the aid of models such as FLO-2D once the magnitude of the flow event and the properties of the fluid-sediment mixture have been determined. b) Public regulations, zoning and development avoidance on alluvial fans is often indicated. Public awareness is possible at all times. For instance, communities developing on alluvial fans can be informed anytime about preventive measures, insurance and community improvement plans. At the onset of large events, people should be informed, kept away or evacuated from potentially hazardous areas prone to possible structural failure. 2. It is clear that in mudflows with bouldery fronts, the boulders do not generate fluid motion, but it is rather because of the high viscosity of the fluid matrix that boulders can be carried downstream. If you remove the boulders, the fluid maintains its viscous properties and fluid motion is relatively unchanged. The statement was therefore correct in that the coarse grains do not significantly alter the fluid properties of viscosity and yield strength which control the flow condition. The effect of coarse grains on fluid flow is therefore not so important.