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DELINEATION OF LANDSLIDE, FLASH FLOOD, AND DEBRIS FLOW HAZARDS IN UTAH

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PHYSICAL PROPERTIES AND MECHANICS OF HYPERCONCENTRATED SEDIMENT FLOWS

by J. S. O'Brien and P. Y. Julien

ABSTRACT

The authors advance a better understanding of hyperconcentrated sediment flows, commonly referred to as debris flows or mudflows, with a fundamental investigation of the nature of fluid motion. In these flows of large concentrations of sediment, the predominant processes of energy dissipation are related to the viscous, turbulent, dispersive and yield stresses. The relative magnitude of these components largely depend on the fluid properties and whether the flow matrix consists of cohesive or noncohesive sediment. Based on experimental data, the following relationships are provided: 1) stress versus rate of strain, 2) viscosity versus sediment concentration, and 3) yield strength versus sediment concentration. These results expand our knowledge of the physical properties of hyperconcentrated flows.

The authors also review the application of fluid principles to these flows. The fundamentals of fluid mechanics are outlined for the case of hyperconcentrated flows on steep slopes with emphasis on the physical properties of non-Newtonian fluids. A theoretically sound and simplified methodology prescribe the engineering analysis for these hazard flows.

INTRODUCTION

Hyperconcentrated sediment flows are commonly referred to as mud flows or debris flows. The term hyperconcentrated, however, depicts a broader spectrum of sediment transport ranging from large concentrations of suspended sediment in streams to landslides. Sharp and Nobles (1953) refer to hyperconcentrated flows as debris flows instead of mud flows when fifty percent or more of the sediment in the flow matrix is coarser than sand. Debris flows have also been described as granular flows which are identified by the absence of fine material (silts and clays).

Hyperconcentrated flows originate in basins which can be delineated into three zones. The sediment source area is located in the uppermost region of the watershed and may be in a landslide area. The zone of sediment transport is a steep channel system in which erosion and deposition are generally in equilibrium. Finally, the alluvial fan is a depositional zone often identified by a break in the bed slope of the main channel.

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Alluvial fans in the mountain communities of Colorado and Utah have become attractive sites for development; homes, subdivisions and even entire towns are located on the fans of small watersheds. Recent growth and development trends are forcing construction to encroach on apparently inactive fans with devastating results. There has been a dramatic increase in the number of destructive and life threatening encounters with high hazard mud floods and mud flows. The annual cost incurred from these destructive events now exceeds millions of dollars. In 1984 damages in Colorado were estimated at $32 million. There is a critical need to delineate these hazard areas and develop a predictive methodology that will define the level of hazard.

The long-term objective of this research is to develop a predictive mathematical model for hyperconcentrated sediment flows that is manageable and cost effective. The model should be based on a thorough understanding of the physical processes and should predict the following flow properties at desired reach stations: peak discharge, time to peak, average velocity, average flow depth, volume of water and sediment, impact pressure, runout distances, and areas of inundation for a given event frequency.

A steep watershed model for water and sediment routing of overland flow and in open channels using the kinematic wave approximation for the momentum equation has been in use for several years. It remains to link the watershed model with constitutive equations for mud and debris flows, routing them down open channels and across alluvial fans. In addition, a complete model will require description of the mobilization processes of the eroded material which comes off the slope and enters the channels. Such processes may include rill and gully erosion, bank sloughing failure, landslide and overland flow.

The continuing research on hyperconcentrated sediment flows at Colorado State University is directed towards development of a predictive methodology. This requires a thorough understanding of the physical processes of water-sediment mixtures which can only be accomplished through a research program involving theoretical analysis laboratory measurements and field investigation. Initially in this paper, the physical properties of hyperconcentrated sediment flows are defined, followed by a description of the shear stress relationships linked to the mechanics of hyperconcentrated flows. The proposed theoretical developments are supported by laboratory analysis from field samples. A simple methodology has been applied to 16 watersheds to evaluate the relative magnitude of internal to boundary energy losses.

DELINEATION OF HYPERCONCENTRATION SEDIMENT FLOW CATEGORIES

Hyperconcentrated sediment flows encompass a wide range of flow concentration conditions. An attempt to delineate mass wasting processes into several categories with different flow properties was initiated by the National Research Council Committee on Methodologies for Predicting Mud Flows (NRC, 1982). To refine the delineation with some physical properties of the fluid matrix, several experiments were performed at Colorado State University on mud flow samples extracted from undisturbed deposits located in Colorado. The samples were analyzed for size fraction and silt and clay content, and the properties of the mixture were described for various water and sediment concentrations. The results were incorporated into the definitions promulgated by the NRC committee and are shown in Table 1.

In nature, there exist a continuum of flow conditions and one hydrologic event may consist of several flow processes. Flow deposits, scour characteristics, and fan patterns are helpful tools in identifying the flow regimes and processes. Although the transition between the different types of flow are difficult to distinguish, mass wasting processes can be divided in four main categories: water floods, mud floods, mud flows, and landslides.

Conventional water flooding is defined as water inundation by overbank discharge. Sediment is transported through the mechanisms of suspension and rolling and saltation along the bed which depend largely on water velocity and turbulence. For water floods, standard hydrologic and sediment transport capacity methods and formulas are applicable. Water floods are not a phenomena analyzed in this paper.

Mud floods define a range of concentration from 20 to 45 percent by volume (Table 1). This concentration refers to the fluid matrix and should be assumed to consist of silts, clays and fine sands only. Water floods and mud floods display inherent fluid properties, both are unable to resist shear stress without motion or exhibit any appreciable yield strength. Conventional analysis using momentum, energy and continuity equations are applicable. Sediment transport capacity equations such as Einstein and Meyer-Peter and Müller are inappropriate because higher viscosities of the mixture and lower fall velocities of solid particles invalidate the empirical constants which are based on clear water as the fluid medium. Water floods and mud floods are classified under the National Flood Insurance Program (NFIP) definition of floods by the NCR (see Figure 1).

In mud flows the sediment concentration is sufficient to support large clastic material in a quiescent condition without settling. The flow matrix exhibits a distinct resistance to motion (high yield strength). This resistance to shear stress is a pseudo-plastic flow property corresponding to high viscosities. The National Research Council (NRC, 1982) report states, "The key characteristic in differentiating between mud floods and mud flows is that a mud flow displays a combination of density and strength that will support inclusions of higher density than water, such as boulders, both during transport and when the mass comes to rest". Throughout the flow process the combination of fluid matrix density and small settling velocities keep the boulders near the surface in the absence of turbulence. In steep basins, mud flows are generated under certain conditions of rainfall and sediment availability. When unlimited supplies of sediment become available, the probability of producing a mud flow is very high for intense rainfall events. Debris flows are acknowledged as having more than fifty percent of the sediment sizes coarser than sand. Debris flows without fine materials (silts and clays) are referred to as granular flows.

TABLE 1. DESCRIPTION OF HYPERCONCENTRATED SEDIMENT FLOW AS A FUNCTION OF CONCENTRATION†

Flow Type	Concentration by Volume C_v	Concentration by Weight C_w *	Flow Characteristics
Landslides	.53-.90	.75-.96	Will not flow, failure by block sliding
	.50-.53	.73-.75	Block sliding failure with internal deformation during the slide, slow creep prior to failure
Mud Flows	.48-.50	.72-.73	Flow evident, slow creep sustained mud flow, plastic deformation under its own weight, cohesive, will not spread on level surface
	.45-.48	.69-.72	Begins spreading, cohesive
Mud Flood	.40-.45	.65-.69	Mixes easily, shows fluid properties in deformation; spreads on horizontal surface but maintains a inclined fluid surface, large particle settling, waves appear but dissipate rapidly
	.35-.40	.59-.65	Marked settling, spreading nearly complete on horizontal surface, liquid surface two phases appear, waves travel substantial distance
	.30-.35	.54-.59	Separation of water on surface, two phases, waves travel easily, most sand and gravel has settled out
	.20-.30	.41-.54	Distinct wave action, fluid surface, all particles resting on bottom in quiescent fluid condition
Water Flood	<.20	.41	Water flood with bed and suspended loads

†This information is qualitative guideline in which the concentration refers to the fluid matrix consisting of silts, clays and fine sands.

*The concentration by weight is computed using 2.72 as the specific gravity for the sediment as measured in the laboratory.

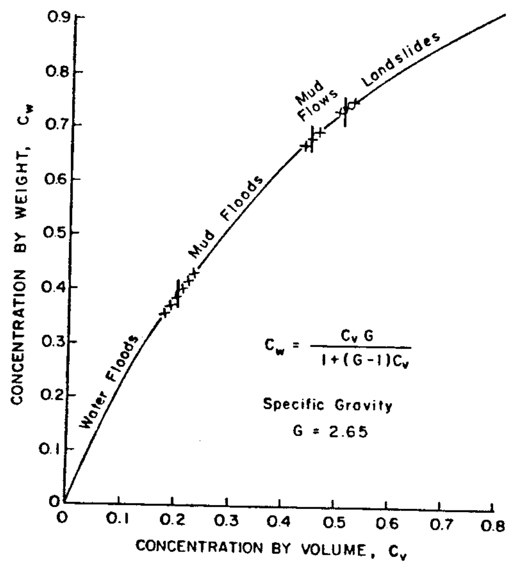

FIGURE 1. HYPERCONCENTRATED SEDIMENT FLOWS CLASSIFICATION

Landslides consist of downslope movement of earth by mechanisms of falling, toppling, sliding and spreading. Such earth movements may be either wet or dry. Landslides and bank slumps are an integral part of generating mud flows and mud floods in steep basins. This mechanism delivers source material to channel in brief singular events that often perturbate the channel flow hydraulics.

PHYSICAL PROPERTIES OF THE FLUID MATRIX

The presence of large concentrations of sediment induces complex processes of energy dissipation in the fluid matrix. Besides the viscous and turbulent stresses existing in clear water flows, the interaction of water and sediment, the exchange of sediment particles with the channel boundary, and the collisions of suspended particles (dispersive stress) all contribute to the dissipation of energy from the fluid matrix. Moreover, the presence of clay particles whose cohesive forces arise from hydrophilic bonding, modifies the physical processes governing the fluid flows. Hyperconcentrated sediment flows, therefore, are a function of complex interrelationships between water and sediments which require further investigation.

Conventionally, the force in fluids necessary to produce a given deformation is proportional to the rate of deformation. For a real fluid in motion relative to a rigid boundary, shear stresses develop in proportion to the rate of angular deformation. This definition implies that shear stresses will exist only in moving fluids. Figure 2 shows different relationships between shear stress and the rate of deformation.

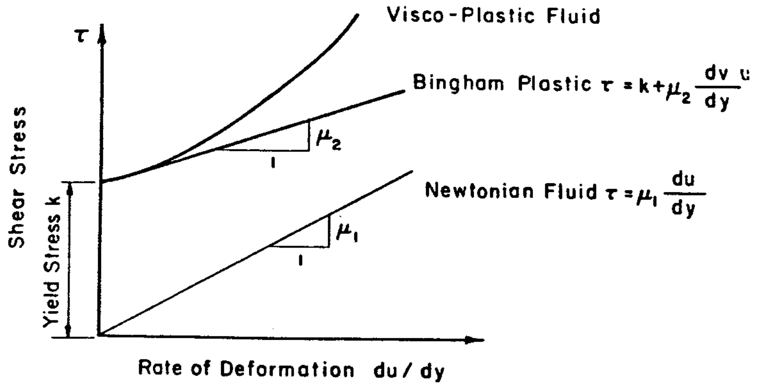

FIGURE 2. BEHAVIOR OF FLUIDS

Newtonian fluids follow a linear relationship between shear stress and rate of strain in which the slope of the line is the viscosity μ of the fluid. The Bingham plastic model combines a yield stress k and a linear stress-strain relationship for shear stresses in excess of the yield value. Hyperconcentrated flows are non-Newtonian, the shear stress exhibited by the flow is not proportional to a linear rate of strain. Bingham plastic and visco-plastic relationships are commonly used to describe hyperconcentrated flows. The property of a yield stress which must be exceeded to initiate motion gives rise to the plastic or Bingham nature of the fluid.

In the analysis of most rivers and streams, the sediment being transported has negligible effect on the Newtonian properties of the fluid (water). In mud flows, however, large concentrations of fine sediment alter the fluid properties, particularly viscosity and turbulence. For the case of mud flows, the 'fluid' consists of the water and fine sediment and is referred to as the fluid matrix. Mud flows generally transport large clastic material, including large boulders. The clastic material is suspended in the fluid matrix, often being rafted on or near the surface of the flow. The large concentration of fine material (silt and clay) have altered the fluid matrix properties of viscosity and density and, therefore, the lift, drag and buoyancy forces acting on the particle exceed that which would have been exerted by water alone. The fluid matrix consists of the fluid plus the sediment particles which will have a negligible fall velocity in a quiescent condition.

Consider the case of granular flows in which the fluid matrix is water and the sediment is virtually all noncohesive clastic material. Granular flows may be either wet or dry (Passman et al., 1980, Nunziato and Passman, 1980 and Savage, 1979). The fluid medium is water and the fall velocity of the particle is large due to the absence of fines and the corresponding small viscosity of the fluid matrix.

Concentration and flow properties should be expected to change with larger concentrations of silt and clay. Graf (1971) reported that the fall velocity of particles decreases with the addition of fine sediment to water. A small percent concentration by weight of sediment in flowing water dampens turbulent eddies (Vanoni, 1941). Bagnold (1956) further indicated that at high concentrations of sediment, the turbulence may disappear altogether. Increasing the concentration of fines has the effect of increasing both the viscosity and density of the flow. Viscosities of actual debris flow deposits have been measured in the laboratory in excess of 1000 poises (the viscosity of water is about 0.01 poises).

The sediment concentration determines the physical characteristics of hyperconcentrated sediment flows. Concentration can be measured either by weight C_w or by volume C_v with a conversion of

$$C_w = \frac{C_v G}{1 + (G-1)C_v} \tag{1}$$

where G is the specific gravity of dry sediment. A concentration of 50% by volume corresponds to 73% concentration by weight using 2.65 as the specific gravity for the sediment. Referring to Table 1, 50% concentration by volume represents a perceived limit to a mud flow with some fluid properties as determined through laboratory experiments.

It is noteworthy that Bagnold (1954), in his paper on dispersive stress theory, described flows of uniform grains with a concentration by volume of 57% as a granular paste and 52% concentration by volume as the Newtonian fluid limit. In his calculations he correctly reported that the maximum concentration for spheres is 74% by volume with a lower value of 65% for natural, reasonably rounded uniform grains. Using some data from Lamb and Whitman (1969) and Das (1983) the concentrations in Table 2 were computed. The loosest stable arrangement for uniform spheres is a simple cubic structure with a concentration of 53% by volume. The average minimum volumetric concentration of several soil types shown in this table is 54%. For impending fluid motion of the sediment, the concentrations must decrease from these minimum values given in Table 2; otherwise the sediment would move as a block. This evidence supports the delineation of flow definitions indicated in Table 1.

TABLE 2. CONCENTRATION BY VOLUME OF GRANULAR SOILS
(Modified After Lamb and Whitman, 1969 and Das, 1983)

Description	C_v Minimum		C_v Maximum
Uniform Spheres	0.53		0.74
simple cubic configuration		0.53	
bodied-centered cubic		0.68	
face-centered cubic		0.74	
hexagonal close-packed structure		0.74	
Uniform Inorganic Silt	0.48		0.61
Standard Ottawa Sand	0.56		0.67
Clean Uniform Sand	0.50		0.61
Silty Sand	0.53		0.78
Fine Sand	0.54		0.71
Coarse Sand	0.57		0.74
Fine to Coarse Sand	0.51		0.83
Micaceous Sand	0.45		0.71
Silty Sand and Gravel	0.54		0.88
Gravelly Sand	0.59		0.83
Gravel	0.63		0.77
Average	0.54		

In the field, higher concentrations may be possible with larger quantities of silt and clay in the flow matrix. Written accounts of mud flows describe a wide range of concentrations with maximum concentrations by weight as high as 79 to 85% (Sharp and Nobles, 1953), 60 to 78% (Pierson, 1981) 59 to 86% (Pierson, 1980), 60 to 90% (Johnson, 1970) and 91% (Curry, 1966). Any loss of water during the sampling process, however, could result in significantly higher concentrations than actually occurred during the flow events. Surges and nonuniformity in the flow concentrations also distort the measured estimates of the flow properties. It is suggested that attempts at reporting mud and debris flow events should focus on a description of the mean flow properties which will assist in developing future predictive methods.

MECHANICS OF HYPERCONCENTRATED SEDIMENT FLOWS

The predominant processes of energy dissipation and resistance to motion are a function of the viscous, turbulent, dispersive and yield shear stresses. The relative magnitude of these stresses largely depend on the fluid properties, the concentration of sediment and whether the flow matrix includes cohesive sediment. Although the initiation of motion through landslides and creeping soil failures are more properly examined through a soil mechanics approach, the hyperconcentrated flows should be analyzed in a continuum approach to describe a wide range of concentrations ranging from clear water to very viscous mud flows.

Newton's second law is applied to describe the one-dimensional motion of an incompressible water-sediment mixture. The force equilibrium per unit mass may be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = g\sin\theta - \frac{1}{\rho_m}\frac{\partial p}{\partial x} + \frac{1}{\rho_m}\frac{\partial \tau}{\partial y} \qquad (2)$$

where ρ_m is the density of the fluid mixture, u is the velocity in the downstream x-direction, p is the internal pressure, τ is the shear stress, g is the gravitational acceleration, $\sin\theta$ is the channel slope and y is the upward distance above the channel bed perpendicular to the flow. The left side of the equation represents the local and convective acceleration of the fluid. These terms depict the unsteadiness and nonuniformity of the flow. The right side of the equation represents the gravity, pressure, and resistive shear stress terms. In the original Navier-Stokes equation valid for Newtonian fluids, the pressure distribution can be assumed to be hydrostatic and the shear stress is a function of the viscosity μ and of the rate of deformation

$$\tau = \mu\frac{\partial u}{\partial y} \qquad (3)$$

In mud flows, however, the shear stress is a complex function of the water and sediment properties comprising the fluid matrix which limits its direct application for predictive modeling. A general equation postulated for the resistive shear stress in a water sediment mixture is

$$\tau = k + \mu_m\frac{\partial u}{\partial y} + C_1\left(\frac{\partial u}{\partial y}\right)^2 + \ldots \qquad (4)$$

where k is the yield stress, μ_m is the viscosity of the fluid matrix and C_1 may be a variable whose magnitude depends on depth and concentration. The combination of the first two terms is referred to as the Bingham model for mud flows. The Bingham model consists of a yield stress term and a viscous stress term. This model is applicable when the applied shear stress exceeds the yield stress ($\tau > k$) and the resistive stress is linearly proportional to the rate of strain. Both the yield stress k and the viscosity μ_m are functions of concentration as shown in Figures 3 and 4. The Bingham model can be used somewhat successfully to describe the motion of mud flows in smooth prismatic open channels for partially turbulent or transitional flows without energy losses due to roughness.

The $C_1(\frac{\partial u}{\partial y})^2$ term is a composite of the dispersive and turbulent stresses. It is referred to as the inertial term in the shear stress equation. The conventional representation for the turbulence stresses in clear water is

$$\tau_R = \rho\,\kappa^2\,y^2\left(\frac{\partial u}{\partial y}\right)^2 \qquad (5)$$

in which ρ is the density of clear water and κ is the von Karman constant. The dispersive stress arising from the collision of sediment particles as defined by Bagnold (1954) is

$$\tau_D = a_i\,\lambda^2\,D_s^{\,2}\left(\frac{\partial u}{\partial y}\right)^2 \qquad (6)$$

where D_s is a representative grain diameter and a_i is a constant. The linear concentration λ can be written as a function of the concentration by volume C_v and the maximum possible static concentration by volume C_o

$$\lambda = \frac{1}{(C_o/C_v)^{1/3}-1} \qquad (7)$$

In a water and sediment mixture, these two stresses can be combined in Eq. 4 since both are functions of the second power of the rate of deformation. The turbulent stresses assist in suspending particles into the flow by exchanging momentum from the fluid to the sediment particles. The dispersive stresses meanwhile, impart momentum transfer between the particles. Increasing concentration and the corresponding collisions between the particles dampens turbulence. A characteristic of turbulence is the irregular or random motion of a fluid which generates pseudo-stresses in the sense that they originate from the acceleration terms. The momentum is transferred to the boundary by viscous diffusion (vorticity). The flow is mixed through eddies and the stretching of vortices create smaller eddies and drive the interaction between eddies of different sizes. High sediment concentration dampens

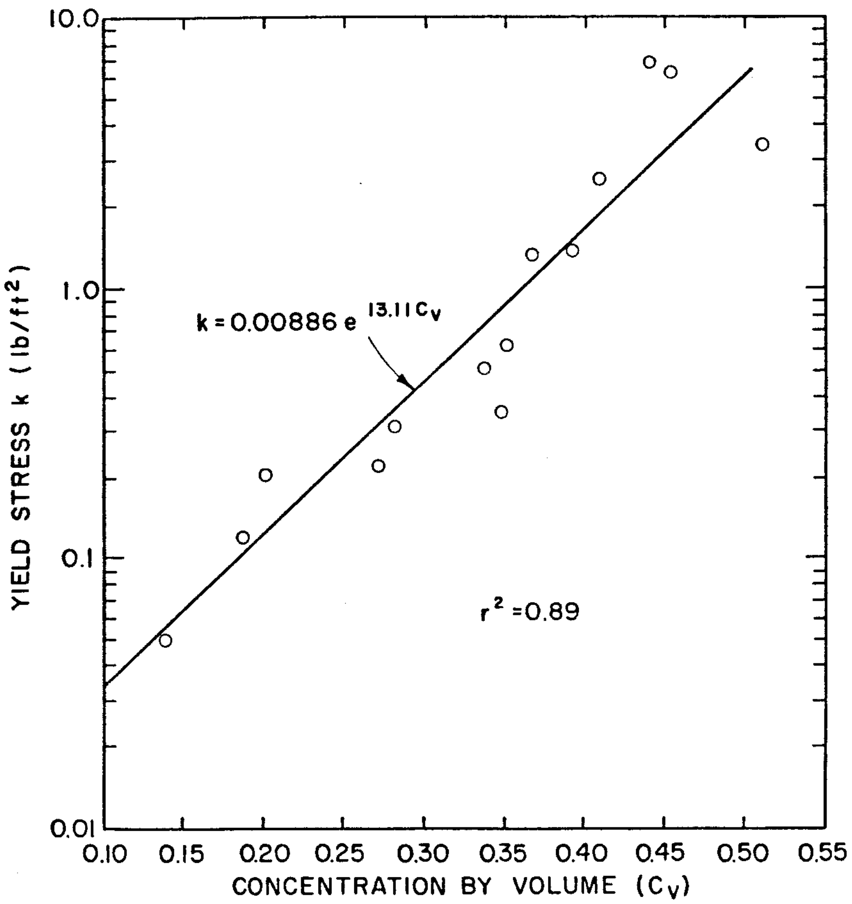

FIGURE 3. YIELD STRESS vs. CONCENTRATION BY VOLUME

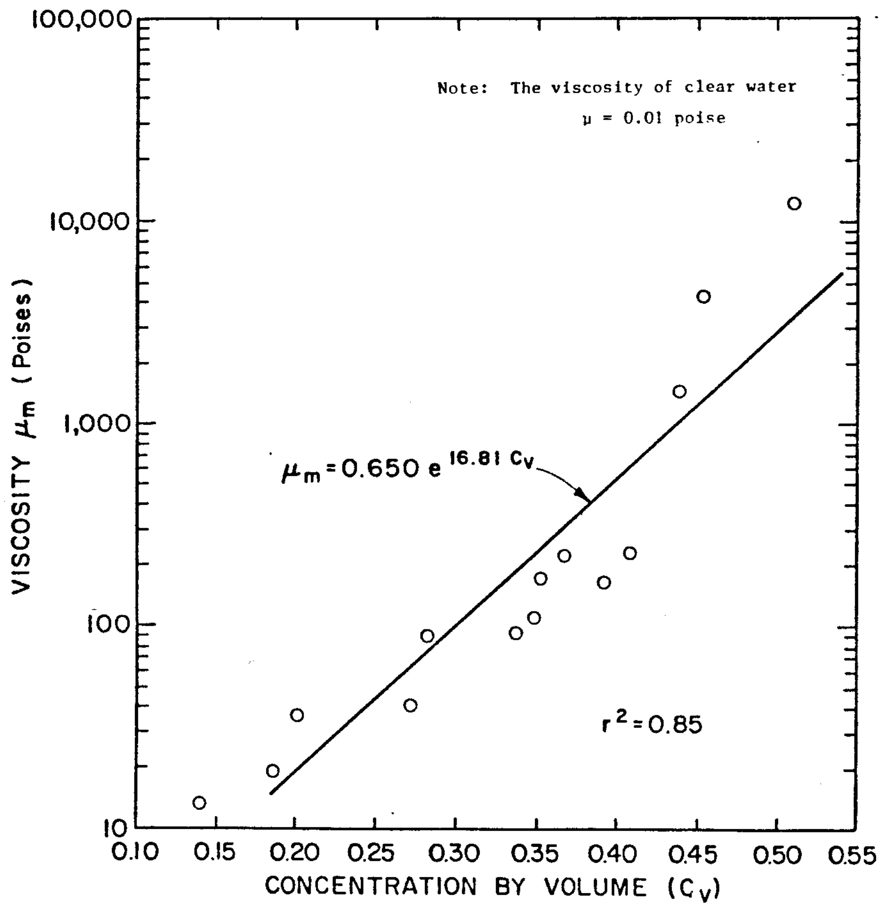

FIGURE 4. VISCOSITY vs. CONCENTRATION BY VOLUME

the eddies in a cumulative manner dissipating the smaller eddies first or hampering their formation altogether. Sharp and Nobles (1953) noted this phenomena in their descriptive paper. In this fashion, the energy is sapped from the main body of the flow and expended to increase the sediment particle velocity and the height of suspension. This energy is distributed throughout the various levels of the flow and is eventually lost in the fluid mixture through viscous heat.

The turbulence and dispersive stresses lose their separate identities in a hyperconcentrated sediment flow and both stresses can be combined in the last term of Eq. 4. The stress-strain relationship given by Eq. 4 is promoted as correctly representing the behaviour of hyperconcentrated sediment mixtures. This relationship is theoretically sound since it is derived from fundamental principles in fluid mechanics, and the parameters of this function represent physical quantities. The relative magnitude of these parameters depends on the composition of the water-sediment mixture which can be described by (the concentration by weight C_w or the concentration by volume C_v and the concentration of fine material C_f.

Equation 4 was tested in laboratory analysis using a rotating viscometer to measure the stress-strain relationship of a fluid matrix from a mud flow deposit. The results are shown in Figure 5. The physical properties defined by the relationship are the yield stress (k = 0.0108 lb/ft^2), the viscosity of the fluid matrix (μ_m = 0.00065 lb-s/ft^2 = 0.31 poises) and C_1 = 0.0065 lb-s^2/ft^2. The viscosity of the mixture is about thirty times larger than that of clear water. The parabolic relationship defined by regression analysis generates a better fitting curve (r^2 = 0.98) than a linear relationship between stress and strain rate (r^2 = 0.95). The Bingham model erroneously predicts a viscosity (9.43 poises) thirty times larger than the Eq. 4.

The ratio R of the inertial stress term to the viscous stress, the last two terms on the right side of Eq. 4, is

$$R = \frac{C_1}{\mu_m} \frac{\partial u}{\partial y} \qquad (8)$$

This non-dimensional ratio defines the relative magnitude of the inertial to viscous stresses in a form similar to the Rouse number for clear water turbulent flows. This ratio supercedes the use of any critical Reynolds number which is not applicable to delineate non-Newtonian flow regimes. A small value of R indicates the predominance of viscous stresses and suggest the use of a Bingham model rather than the complete solution of Eq. 4. The value of C_1 is determined through laboratory analysis from Figure 3 and is a function of the sediment concentration, particle diameter, flow depth and clay concentration.

Similarly the Bingham number can be written as the ratio of the yield stress to the viscous stress

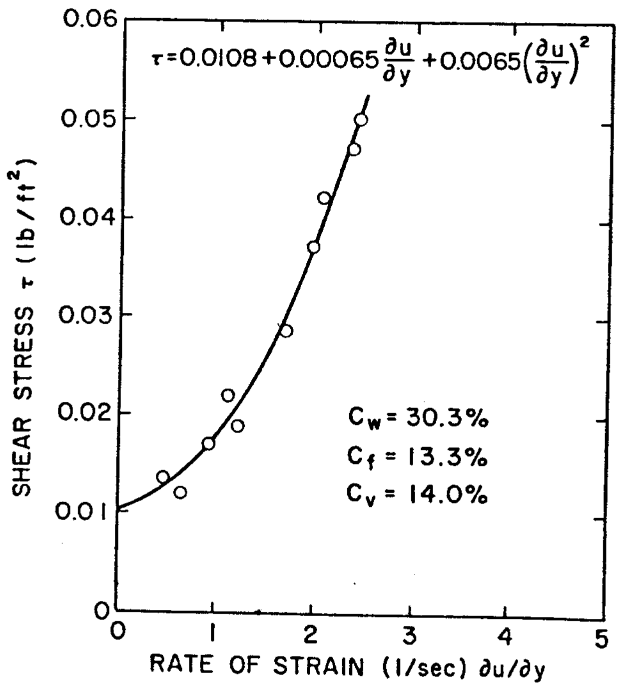

FIGURE 5. SHEAR STRESS vs. RATE OF STRAIN

$$B = \frac{k}{\mu_m}\frac{\partial \dot{y}}{\partial u} \quad (9)$$

This ratio indicates the relative magnitude of the yield and viscous terms. As R becomes small and B reduces to zero, the fluid will behave as a Newtonian fluid. These two ratios R and B are valid at every point along a velocity profile since they are both a function of $\frac{\partial u}{\partial y}$. In order to describe the mean flow characteristics, however, the partial derivative $\frac{\partial u}{\partial y}$ can be replaced by the ratio of average velocity $\bar{u}$ to the flow depth d in Eqs. 8 and 9. Both ratios must be defined by laboratory investigation.

APPLICATIONS

The physical processes encountered in mud flows are extremely complex. Valuable insight into the real nature of these non-Newtonian flows was gained through theoretical work, laboratory analysis and field investigations. Simplified methodologies based on the dominant physical processes have been applied to 16 small steep watersheds generating mud flows near Glenwood Springs, Colorado. One objective was to determine the relative magnitude of the losses attributed to internal viscous dissipation as compared to the losses due to channel boundary roughness. This analysis is based on the force balance equation (Eq. 2). The pressure term is written as a function of flow depth d and the shear stress τ in the channel is subdivided in two components. The first component τ_b is due to the large boundary roughness elements written as a function of the boundary energy loss gradient S_b and the second accounts for the internal stress τ_i. Assuming an hydrostatic pressure distribution in a one-dimensional flow over rough boundaries, Eq. 2 can be rewritten as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial d}{\partial x} - g\sin\theta + g S_b + \frac{1}{\mu_m}\frac{\partial \tau_i}{\partial y} = 0 \quad (10)$$

The solution to this equation when combined with the continuity equation gives a complete one-dimensional dynamic description of the motion of hyperconcentrated sediment flows. Steady uniform flow conditions can be assumed which eliminates the first three terms of Eq. 10, the internal energy gradient S_i is then defined as

$$S_i = \frac{1}{\rho_m g}\frac{\partial \tau_i}{\partial y} = S_o - S_b \quad (11)$$

where the bed slope (sinθ) is written as S_o. The boundary friction slope term S_b is important because the large boundary roughness elements force the fluid mixture to flow around boulders, trees and other channel obstacles, thus creating additional losses which enhance the C_1 term in Eq. 4. In this manner, energy is first transformed into turbulence and then dissipated in viscous heat. These energy losses S_i and S_b are treated separately for the purpose of this discussion. The shear stress can be written, in a first approximation, as a function of the mean flow velocity u, depth d and resistance coefficient c_b

$$\tau_b = \rho_m g\, d\, S_b = c_b\, \rho_m\, \bar{u}^2 \quad (12)$$

This equation leads to a Chézy type of relationship which can be transformed into the more widely used Manning's type of equation

$$S_b = \left(\frac{n\,\bar{u}}{1.49\, d^{2/3}}\right)^2 \quad (13)$$

in which the equivalent Manning n value is derived from Eq. 12

$$n = 1.49\sqrt{\frac{c_b}{g}}\, d^{1/6} \quad (14)$$

The friction slope given by Eq. 13 is a function of the flow depth and velocity. These two variables were computed by assuming that the internal stress, obtained after integrating Eq. 11, obeys a Bingham plastic model such that

$$\tau_i = \gamma_m\,(S_o - S_b)(d-y) = k + \mu_m \frac{du}{dy} \quad (15)$$

The mean velocity is then obtained by integration along the flow depth d

$$\bar{u} = \frac{1}{d}\int_0^d \int_0^y \frac{du}{dy}\, dy\, dy = \frac{\gamma_m (S_o - S_b) d^2}{3\mu_m} - \frac{kd}{2\mu_m} \quad (16)$$

After substitution of Eq. 13 into Eq. 16, and satisfying the continuity relationship $q = \bar{u}d$, these equations were solved by iteration to obtain $\bar{u}$ and d. The substitution into Eq. 13 then gives the boundary friction slope S_b.

The magnitude of the internal stresses as determined from Eq. 11 can be compared to the magnitude of the boundary roughness stresses expressed as a percentage of the bed slope using the following ratio

$$R_s = \frac{S_i}{S_o} = \frac{S_o - S_b}{S_o} \quad (17)$$

Table 3 represents the mean values of R_s as a function of concentration for 16 different basins analyzed in the vicinity of Glenwood Springs, Colorado, for three different return period floods (10 year, 25 year and 100 year). This table shows a very rapid increase of R_s at concentrations larger than 0.44 and similar trends are observed for the three flood events. These conclusive results indicate that for concentrations smaller than 0.42 the energy losses are mainly the result of channel roughness. For larger concentrations, however, the internal losses are increasingly important in the role of energy dissipation.

TABLE 3. RATIO OF INTERNAL TO BOUNDARY ROUGHNESS STRESSES R_s

C_v	Flood Event Return Period in Years: 100	25	10
.36	2.2*	2.3	2.7
.38	3.3	4.0	4.9
.40	5.3	6.6	8.2
.42	9.5	11.9	14.6
.44	17.0	20.8	24.9
.46	30.0	36.4	42.3
.49	48.2	57.0	63.5
.51	71.5	78.1	82.7
.54	88.3	92.3	94.2

*R_s values in percent, Standard Error ranged from 0.3 to 3.9%

This simplified analysis reveals the importance of the physical properties of the fluid matrix and prescribes the need for more fundamental research on mud flows. Ignoring either the viscous or friction slope term in the analysis would result in the overprediction of the velocity of the flow. There are inaccuracies in this analysis. First, the Manning's equation is only applicable for fully developed rough turbulent flows. Second, the Bingham model is not applicable for high velocity, rough turbulent flow. Mud flows and debris are inherently unsteady, nonuniform flows. On steep slopes, using the kinematic wave analogy, equation (15) should be solved using the three terms of Eq. 4 and this requires the use of C_1. More experimental analysis is required for the evaluation of C_1 and its variability with concentration, sediment size and boundary roughness. A stainless steel viscometer has been designed for this purpose.

CONCLUSION

The devastating effects of hyperconcentrated sediment flows in the past demonstrate an urgent need for a predictive methodology to define the hazard levels and to aid in the design of adequate mitigations measures and structures. Such a methodology would rely on an accurate knowledge of the physical properties of the water-sediment mixture. Research efforts must be focused on fundamental investigations involving both theoretical and experimental analysis.

This paper emphasizes the physical properties of hyperconcentrated sediment flows. Flow descriptions have been classified as a function of the concentration of sediments. Various experimental, theoretical and field data show that the maximum concentration by volume for mud flows is unlikely to be in excess of 0.50.

Basic fluid mechanics principles are recommended to describe the broad continuum of hyperconcentrated flows. A simple quadratic model (Eq. 4) is postulated, in which each term represents a well-defined physical property of the fluid. The last term of this equation

represents the inertial losses and requires further investigation. Physical meaning of this term, however, has been demonstrated to be associated with turbulent and dispersive stresses in the fluid matrix and has been verified experimentally. Empirical relationships between yield stress, viscosity and the concentration by volume were obtained from laboratory analysis of mud flow samples.

A simplified methodology, applied on 16 small steep watersheds near Glenwood Springs, Colorado, showed that at low concentrations by volume (C_v < 40%), the energy losses are controlled by boundary roughness. For larger concentration, the internal energy losses rapidly become dominant. For the mathematical routing of open channel flows both a macro- and microscopic fluids approach must be applied. The macroscopic approach is needed for energy dissipation attribued to channel roughness. The real energy losses occur in the form of heat dissipation from the viscous interaction between water and sediment particles. The viscous energy dissipation is enhanced by turbulence which, in turn, is promoted by boundary roughness.

Continuing research at CSU on hyperconcentrated flows will focus on the complex physical processes of hyperconcentrated sediment flows preparing the foundation for the eventual mathematical routing of these flows in open channels.

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LIST OF SYMBOLS

a_i	coefficient of the dispersive stress equation
B	Bingham number
c_b	resistance coefficient for boundary roughness
C_o	maximum possible concentration by volume
C_1	coefficient of the inertial stress term
C_f	concentration of fines
C_v	concentration by volume
C_w	concentration by weight
d	flow depth
D_s	representative grain diameter
g	gravitational acceleration

G	specific gravity of sediments
k	yield stress
p	internal pressure
r^2	coefficient of determination
R	ratio of inertial stress to viscous stress
R_s	ratio of internal stress to boundary roughness stress
S_b	boundary energy gradient
S_i	internal energy gradient
S_o	bed slope
t	time
u	velocity
$\bar{u}$	mean velocity
x	longitudinal coordinate (positive downstream)
y	upward distance above the channel bed
κ	von Karman constant
θ	angle of the channel with the horizontal
λ	linear concentration
μ_m	dynamic viscosity of the mixture
ρ	density of clear water
ρ_m	density of the fluid mixture
τ	shear stress
τ_b	shear stress from the boundary roughness
τ_D	dispersive stress
τ_i	internal stress
τ_R	turbulence stress

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