MUD FLOODS, MUDFLOWS AND DEBRIS FLOWS CLASSIFICATION, RHEOLOGY AND STRUCTURAL DESIGN

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ABSTRACT

Hyperconcentrated sediment flows have been classified as mudfloods, mudflows and debris flows. Distinct physical processes differentiate these types of hyperconcentrations based on the rheology of the water-sediment mixture. Four types of shear stresses describe hyperconcentrations: (1) the yield strength; (2) the viscous stress; (3) the turbulent shear stress of the fluid at low sediment concentrations; and (4) the dispersive stress due to the inertial impact of large sediment particles. The yield and viscous stresses depend on the cohesion of fines. The dominant shear stress from these four components depends on volumetric sediment concentration and the amount of fine sediment. A classification of hyperconcentrations based on the rheological properties of the mixture is recommended. Mudfloods are flows where the turbulent shear stress is dominant. Mudflows are flows with predominant yield and viscous stresses. Debris flows correspond to flows where the dispersive stress is dominant.

Mitigation structures require knowledge of the rheological properties of the hyperconcentrated sediment flow. Different mitigation strategies should be considered for mudfloods, mudflows and debris flows. Turbulent mudfloods should be conveyed in straight channels with minimal frictional resistance. For viscous mudflows, flood hazard mitigation should consider detention basins for small volumes and deflection walls for large volumes. High momentum debris flows require sabo dams.

INTRODUCTION

Hyperconcentrated sediment flows can be initiated by numerous causes including intense rainfall, rapid snowmelt, volcanic and man-made activities. The sediment load may also be increased by hillslope failure and bank collapse during flood events. The volume and properties of the fluid matrix, which is comprised of the fluid and sediment particles, govern flow hydraulics, flow cessation and runout distances of hyperconcentrated sediment flows. The fluid matrix properties are usually dependent on sediment concentration, size fraction and clay content.

Mud floods are typically hyperconcentrations of non-cohesive particles (e.g. sand). They display very fluid behavior for the range of sediment concentrations by volume C_v as high as 40%. Mud floods are turbulent and flow resistance depends on boundary roughness as for turbulent flows with clear water. At volumetric sediment concentrations $Cv > 0.05$ the sediment concentration of small particles tends to become more uniform than described by the Rouse vertical concentration profiles. Increased buoyancy and fluid viscosity reduces the settling velocity of sediment particles. A detailed analysis of hyperconcentrations of sands was presented by Woo et al.

(1988). Turbulent diffusion and settling fluxes are dominant despite an increase in specific weight and viscosity of the mixture.

Mudflows are characterized by a sufficiently high concentration of silts and clays (sediment size< 0.0625 mm), which changes the properties of the fluid matrix and helps support large clastic material. Mudflows behave as a highly viscous fluid mass, which at high concentrations is capable of rafting boulders near the flow surface. Based on laboratory results, the volumetric sediment concentration of a mudflow fluid matrix ranges from approximately $45\% < Cv < 55\%$ (O'Brien, 1986). Mudflows exhibit high viscosity and yield stress, can travel long distances on mild slopes at slow velocities and leave lobate deposits on alluvial fans. A detailed rheological analysis of mudflow properties has been presented by O'Brien and Julien (1988), Major and Pierson (1992), and Coussot (1997).

Debris flows are referred to as a mixture of clastic material including boulders and woody debris where lubricated inter-particle collision is the dominant mechanism for energy dissipation. Knowledge of debris flows is based largely on the contributions of Bagnold (1954) and Takahashi (1978). Granular flows (non-cohesive flows without a lubricating fluid) constitute a sub-class of debris flows in which the exchange of momentum between the flow core and the boundary occurs exclusively through particle collision and friction. A comprehensive rheological analysis of granular flow properties has been performed by Mih (1999).

The objective of this paper is to delineate broad guidelines for the design of mitigation countermeasures based on the dominant rheological features of hyperconcentrations. The rheological characteristics of mud floods, mudflows and debris flows are reviewed with the intent to provide guidance as to what type of structure may be appropriate in the design of countermeasures.

RHEOLOGY OF HYPERCONCENTRATED SEDIMENT FLOWS

The general flow behavior of hyperconcentrated sediment flows can be inferred from an examination of the physical processes triggering hyperconcentrations in a watershed, an assessment of sediment availability and sediment source, an investigation of historical flood events on the same or neighboring watershed, and a rheological and particle size analysis of deposits. Deposits from historical or recent events can be brought to the laboratory for a rheological investigation at various sediment concentrations. Rheological analyses involve four different types of shear stresses: 1) yield stress; 2) viscous stress; 3) turbulent stress; and 4) dispersive stress. The non-Newtonian nature of hyperconcentrated sediment flows results from several physical processes: the cohesive yield strenght τ_c, which accounts for the cohesive nature of fine sediment particles; the Mohr-Coulomb shear τ_{mc}, the viscous shear stress τ_v, which accounts for the fluid-particle viscosity; the turbulent shear stress τ_t, and finally, the dispersive stress τ_d which accounts for the collision of the largest fractions or clasts.

The total fluid shear stress τ in hyperconcentrated sediment flow results from the sum of the five shear stress components:

$$\tau = \tau_{mc} + \tau_c + \tau_v + \tau_t + \tau_d \qquad (1)$$

A quadratic rheological equation describes the flow continuum through the range of sediment concentration for these shear stresses. When written in term of shear rates, or velocity gradient du/dy; τ_{mc} and τ_c are independent of velocity gradient, τ_v varies linearly with the velocity gradient and both τ_t and τ_d vary with the second power of the velocity gradient. O'Brien and Julien (1985) and Julien and Lan (1991) proposed the following quadratic rheological model:

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

where $\tau_y = \tau_{mc} + \tau_c$ and $\zeta = \rho_m l_m^2 + a_i \rho_s \lambda^2 d_s^2$

In the above equations η is the dynamic viscosity of the mixture; τ_y is the yield stress; $\tau_{mc}= p_s \tan\phi$ where p_s is the intergranular pressure and ϕ is the angle of repose 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 linear sediment concentration λ (describe below), the mass density of sediment ρ_s and the impact coefficient a_i. 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, the approximate mixing length can be determined by $l_m \cong \kappa h$, where h is the flow depth h and κ=0.4. The coefficient a_i has been shown to be highly variable (Mih, 1999). Bagnold (1954) and Takahashi (1980) proposed $a_i \cong 0.01$. Bagnold defined the linear sediment concentration λ as

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

in which Cv is the volumetric sediment concentration and $C_m \cong 0.615$ is the maximum concentration of sediment particles.

Viscosity η and yield stress τ_y have been generally explained through increasing exponential functions of the volumetric sediment concentration. O'Brien and Julien (1988) measured the rheological properties of natural silt and clay mudflow deposits from the Colorado Rocky Mountains. Their results are in reasonable agreement with those found in the literature (Figures 1 and 2). The yield stress and the viscosity increase by three orders of magnitude as the volumetric concentration increases from 0.10-0.40.

It is important to consider that the occurrence of granular debris flows as prescribed by a dispersive stress relationship alone requires that the following three conditions be simultaneously satisfied: 1) the flow has very large sediment concentrations, e.g. typically $C_v > 0.5$; 2) large velocity gradients, e.g. typically exceeding 100 s^{-1}; and 3) very large sediment particles, e.g. particles sizes coarser than 5% of the flow depth.

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

$$\tau^* = 1 + \left(1 + T_d^*\right) a_i \, D_v^*$$

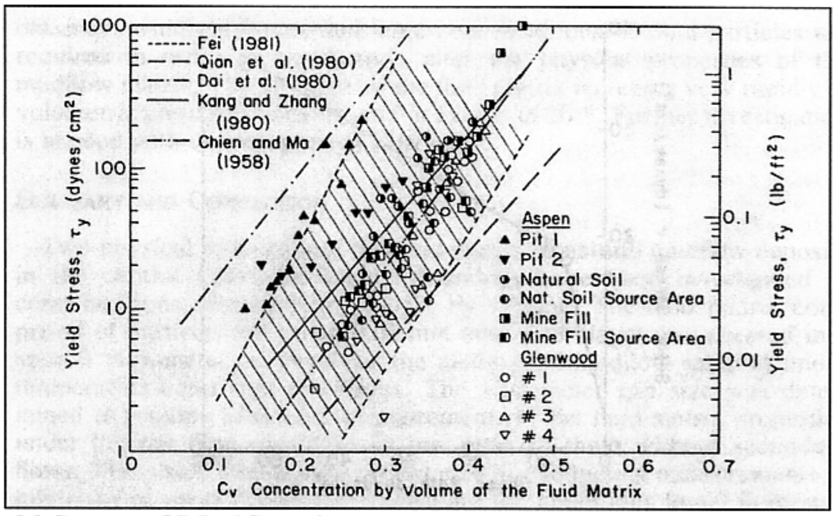

Figure 1. Yield Stress of Mudflow Samples versus Volumetric Concentration (after O'Brien and Julien, 1988)

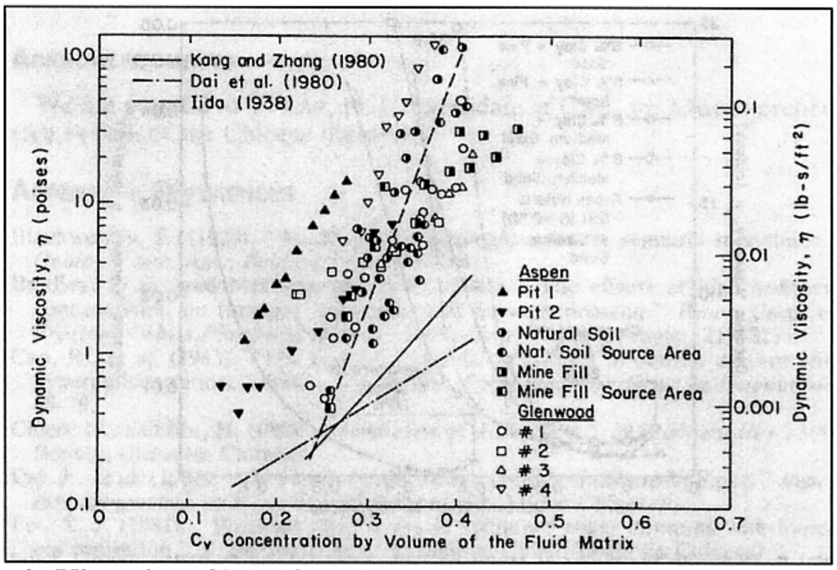

Figure 2. Dynamic Viscosity of Mudflow Samples versus Volumetric Concentration (after O'Brien and Julien, 1988)

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

1. Dimensionless excess shear stress $\tau^* = \dfrac{\tau - \tau_y}{\eta \dfrac{du}{dy}}$. When $\tau^*=1$, the mixture behaves as a Bingham plastic.

2. Dimensionless dispersive-viscous ratio $D_v^* = \frac{\rho_s \lambda^2 d_s^2}{\eta}\left(\frac{du}{dy}\right)$. When D_v^* is large, the flow will be dispersive, when D_v^* is small it is viscous.

3. Dimensionless turbulent-dispersive ratio $T_d^* = \frac{\rho_m l_m^2}{a_i \rho_s \lambda^2 d_s^2}$. Where T_d^* is large the flow is turbulent, when T_d^* small it is dispersive.

Julien and Lan (1991) tested the dimensionless model and the results are in agreement with the data sets from Govier et al. (1957), Bagnold (1954) and Savage and mcKeown (1983) (Figure 3). The quadratic model is valid for all values of the parameter Dv^* and reduces to the Bingham model when $Dv^* < 30$ and to turbulent-dispersive formulations when $Dv^* > 400$.

To relate the parametric delineation to the classification of hyperconcentrated sediment flows, the following guidelines are suggested:

1) Mud floods occur when the turbulent shear stress is dominant as given by $D_v^* > 400$ and $T_d^* > 1$;

2) Mudflows occur when yield and viscous stresses are dominant given by $D_v^* < 30$;

3) Debris flows or granular flows are expected when the dispersive stress is dominant given by $D_v^* > 400$ and $T_d^* < 1$.

A transition regime exists in the range of the parameter $30 < D_v^* < 400$ for which all the terms of the quadratic equation are not negligible. A lengthy description and examples showing the relative magnitude of these terms are presented in Julien (1995) and Hussain (1999).

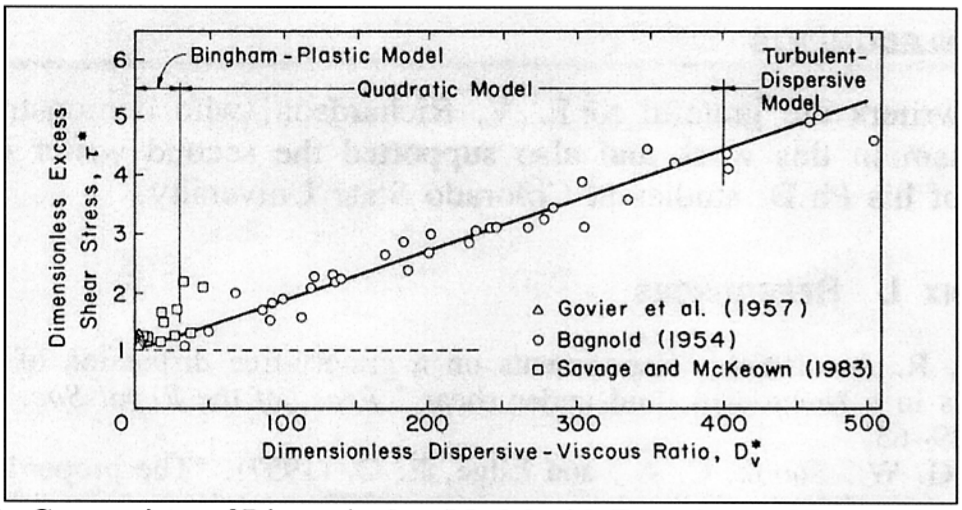

Figure 3. Comparison of Dimensionless Model with Experimental Data (after Julien and Lan, 1991)

NUMERICAL SIMULATION

Based on the quadratic rheological model, the two-dimensional flood routing model FLO-2D for simulation of hyperconcentrated sediment flows from water floods, mudflows and debris flows was developed (O'Brien et al., 1993). The details pertaining to the FLO-2D model are available in O'Brien et al. (1993) and O'Brien and Julien (1997). A manual is available which further discusses the model attributes and its applications. Over thirty flood hazard delineation projects have been completed using the FLO-2D model. O'Brien and Julien (1997) prepared short courses in 1997 and 1998, to make the model available to floodplain managers and engineers.

INFLUENCE OF FLOW RHEOLOGY ON STRUCTURAL DESIGN

Flood mitigation design must take into consideration the rheological behavior of the three types of hyperconcentrated sediment flows previously described, i.e. mud floods, mudflows and debris flows. Flood mitigation measures fall into four categories: 1) flood hazard avoidance; 2) regulation and zoning; 3) storage; or 4) conveyance. The first two categories include such measures as elevating on armored fill, planning open space for flood-prone areas and physically removing structures in the flood path. The last two types include storage and conveyance methods which include detention/debris basins, levees and berms, debris fences and deflectors, sabo dams, channelization and channel lining, drop structures, energy dissipation and street alignment. Mitigation measures for each of the three classes of hyperconcentrated sediment flows are discussed in this section.

Mud Floods

Mud floods are very fluid hyperconcentrated flows in steep mountain channels. Flow velocities are very high and the flow is often supercritical (Figure 4). The fluid matrix viscosity is of the same order of magnitude as that of water. For large storm events on the order of the 100-year storm the volume of water and sediment may exceed the storage of small detention basins constructed in steep watershed canyons. In this case, flood mitigation should focus on the conveyance of the large flood volume off the residential areas, usually located on alluvial fans (Figure 5).

Conveyance design for mud floods should include consideration of sediment bulking, surging (roll waves), supercritical flow, debris plugging, sediment abrasion, superelevation, and potential for sediment scour and deposition. Extra freeboard that commensurate with the velocity head of mud floods should be considered (see Table 1). It is preferable to maintain the channel cross-section as straight and uniform as possible. Straight, steep channels will result in high velocities and high Froude numbers and will prevent the formation of cross waves and local deposition behind channel irregularities.

One of the engineering challenges in the design of straight alluvial channels is the control over the channel path. Streams with high Froude numbers are very erosive and channel migration or avulsion can occur during a flood event. Stability of bed and bank is a critical concern. Using large riprap in steep channels for bank stability is not recommended because the riprap material can be launched by the flow, thus adding to the debris loading. Reducing the slope through drop structures could be effective in controlling the flow, although the erosive potential below drop structures may be excessively high.

Figure 4. Example of mud flood

Type of Flooding	Freeboard (ft)	Impact Factor of Safety
Shallow water flooding < 1 ft	1	1.1
Moderate water flooding < 3 ft	1	1.2
Moderate water flooding < 3 ft, debris and boulders < 1 ft	1	1.2
Mud floods, debris flows, 3 ft, surging, debris, sediment deposition, boulder < 1ft	2	1.25
Mudflows, debris flows, <3 ft, surging, debris, sediment deposition, minor waves, boulders > 1 ft, mud levees	3	1.4
Mudflows, debris flows, > 3 ft, surging, waves, boulders> 3 ft, major deposition	3+	1.5

Table 1. Freeboard and Factor of Safety Recommendations (after FEMA Manual, Chapter 4 (1994 draft), modified) (1m = 3.48 ft)

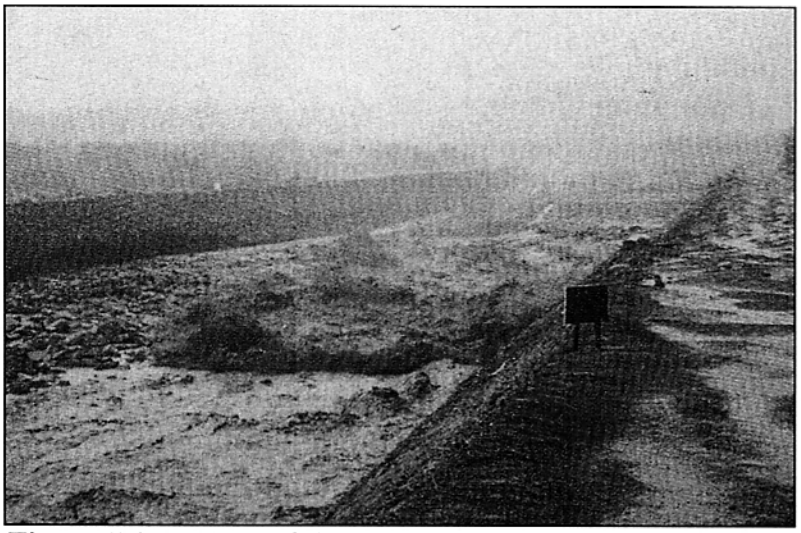

Figure 5. Example of lined channel conveying mud flood

Channel lining with concrete, soil cement or riprap grouting can be effective, but very expensive. Two important design considerations with lining channels on steep alluvial fan slopes are abrasion of the lining and excess pore water pressure. The abrasion of concrete lining occurs with frequent or perennial low flows with high bedload. Failure to consider abrasion during design can shorten the life of the structure and could cause failure during a design flood event. Drain pipes and weep holes can reduce pore water pressure buildup, but construction of channel linings with drain pipes and weep holes can be very expensive for long channel reaches.

The most difficult design task for mud flood channels is to design the inlet and outlet transitions of the straightened reach. At the inlet, a smooth transition is required to avoid flow constriction and debris plugging. Scour and sedimentation may induce failure of the inlet structure. Headwalls and aprons are often necessary at both the inlet and outlets. Without an apron or headwall, local outlet scour can initiate headcuts that will migrate upstream through the straight portion of the channel and undermine channel facilities such as riprap bank protection, and channel drop structures.

In summary, the most effective types of structures to mitigate the effects of mud floods include: 1) straight channels and lined canals; 2) lined berm and levee channels and 3) drop structures and energy dissipators. Detention basin can only be considered when the volume of water and sediment of the design event can be contained. Inappropriate structures against mud floods include debris fences, deflectors and sabo dams.

Mudflows

Mudflows have a fluid viscosity that is several orders of magnitude higher than that of water. Mudflows have low velocities compared to mud floods (Figure 6). Mudflows are more commonly associated with higher frequency, smaller magnitude storm events typically with 10 to 25-year return periods. Larger flood events often have too much water for the available sediment loading in the watershed to generate a mudflow. Extreme mudflow events may degenerate into mud floods. Within a given watershed, the total volume of water and sediment in a mudflow will generally be less than in a mud flood. One exception is volcanically initiated mudflows.

The hydraulic flow properties of mudflows are typically low flow velocities and large flow depths, thus low values of the Froude number. These hydraulic properties sustain motion of mudflows on flat slopes. Flood mitigation design must include consideration of flow avulsion, debris and mud plugging of channel and conveyance facilities, and cleanup/maintenance. Effective mitigation measures for mudflows include storage, deflection, spreading and frontal wave dissipation. Mudflow detention basins can be very effective where mudflow volume is relatively small and can be estimated for the design flood event (Figure 7). When storage capacity is insufficient, a preferred mitigation alternative is to spread the flow over non-urban areas such as open space areas, floodplains, parks and recreation areas where property damages and cleanup costs are minimal. Flow deflection to accomplish flow spreading can be complicated and should consider impact pressures, static loading, and flow runup over previous mud deposits, which could result in overtopping the structure. Possible flow avulsions near the inlet of storage facilities must also be considered as deposits buildup. Deflection of flow into areas that require disposal of the excavated material can be very expensive to operate and maintain.

Figure 6. Typical example of mudflow

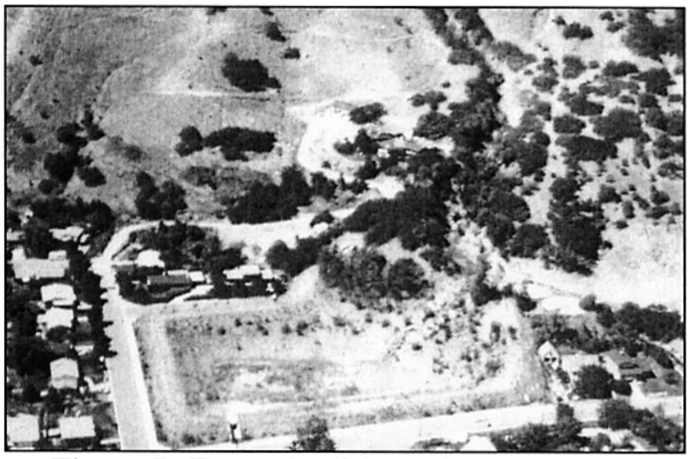

Figure 7. Example of detention basin

Deflection walls can be constructed of concrete, soil cement, or consist of earth berms. Earth berms designed to confine mudflows should have an erosion resistant core or face. Runup and overtopping of berms and walls can be averted by proper orientation of the structure thus deflecting the flow path. Vertical impact faces are also recommended to limit runup. The arrival of a mudflow frontal wave can be very destructive. As part of effective flood hazard mitigation, it is necessary to absorb the high pressure exerted by the frontal wave, which could be carrying large boulders and debris capable of large impact forces and runup against mitigation structures. Impact surfaces should be designed to withstand the impact of the large boulders found on the fan flowing at design depth and velocities. Freeboard design and factor of safety values for impact structures are given in Table 1.

Effective mitigation measures include levees that confine the mudflow outside the channel on the alluvial fan. A portion of the alluvial fan surface can be dedicated to the overbank storage detention. The levee is constructed parallel to the channel allowing an appropriate distance between the channel and berm for mudflow and debris storage; typically 50 ft (15 m) to 100 ft (30 m) can be set aside. The capacity of the conveyance channel is then designed to allow some overbank flow during the peak discharge. Lowering channel banks to create overbank flooding and grading floodplain areas for overbank storage will enhance mudflow deposition. The levee design will generally only require a height of 3 ft (0.9m) to 5 ft (1.5 m), as long as a major change in flow direction is not anticipated. Trees and other obstacles can be left on the floodplain to enhance flow cessation. Potential for levee erosion and failure must be evaluated. A maintenance plan should be prepared to access and remove mudflow deposits between the levees after the event.

Impact loads result from objects entrained in the flow striking a structure surface with a velocity component perpendicular to the flow direction. To compute the impact load, consideration should be given to the evidence of debris and boulders transported on the fan by recent flood events. To be conservative, the largest boulder transported by a flow should be used to determine the impact load. The impact loading P_I is given by:

$$P_I = \frac{wV}{(Ag\Delta t)}$$

where w is the weight of the object, g is the gravitational acceleration, V is the flow velocity, A is the area of impact assumed to be a percentage of the cross sectional area of the object and Δt is the duration of impact. The FEMA Manual (draft, 1994) also presents equations for the computation of the hydrostatic and hydrodynamic loads.

The design of detention basins requires the assessment of the volume of sediment for the design flood event. An acceptable method is to bulk the 100-year hydrograph volume for the potential average concentration of the flow event. Typically, peak sediment concentration by volume for a mudflow event ranges from 45% to 55%, and the average sediment concentration for the flow event is of the order of 25% to 35%. A conservative approach is to use an average concentration of 50% by volume, which results in a bulking factor BF of 2 given by:

$$BF = \frac{1}{(1 - Cv)}$$

In summary, the most effective countermeasures to mudflows are: 1) detention basins and storage methods; 2) deflection walls aiming at spreading out the mud with berms and walls. Less effective methods include: 1) sabo dams; 2) channelization and canal lining and 3) drop structures and energy dissipation methods.

Debris Flows

Debris flows involve the motion of large clastic material and debris characterized by destructive frontal impact surging and flow cessation on steep slopes (Figure 8). Dispersive stress arising from the collision of clastic particles controls the exchange of flow momentum and energy dissipation. Debris flows are much less fluid than mud floods. The fluid matrix viscosity is comparatively small corresponding to the small concentration of fine sediments. The fluid matrix is essentially non-cohesive. The interstitial fluid does not significantly inhibit particle contact, permitting frequent collisions and impact between the solid clasts.

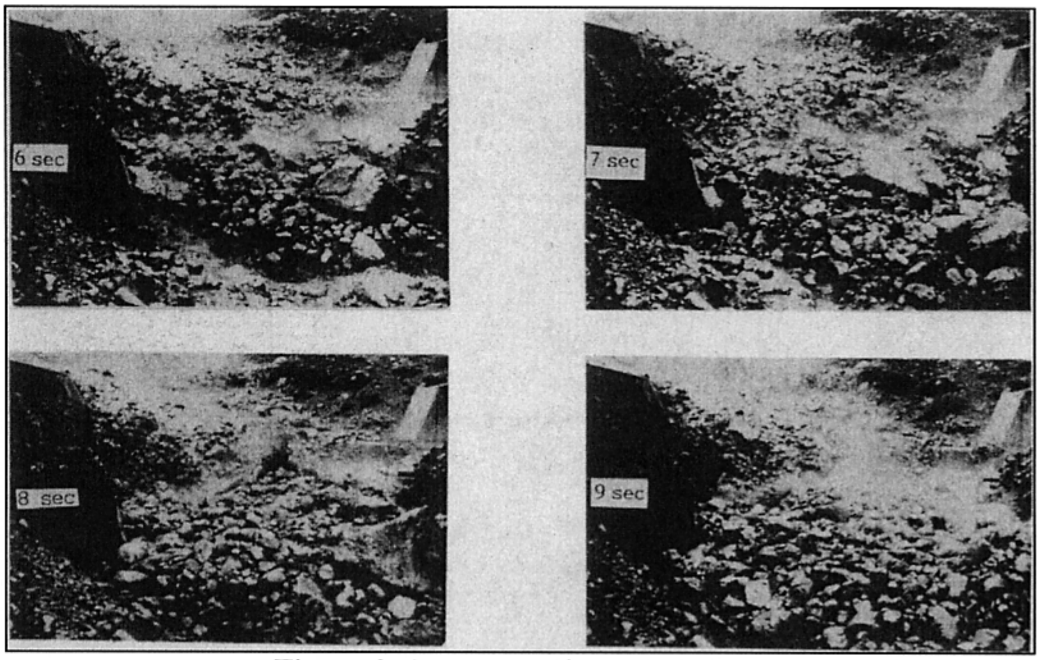

Figure 8. Example of debris flow

Debris flows originate on steep slopes and attain high velocities. The impact forces generated by fast moving coarse material can be exceedingly destructive. Debris flow flood hazard mitigation should be focused on arresting the large clasts and avoiding the destructive impact forces while draining the fluid matrix. A major problem with debris flow mitigation is assessing the volume of the event. Mitigation may be impractical for large events (i.e. 100-year event). Structures such as sabo dams, debris rakes and fences are designed to separate out the debris material (Figure 9). The purpose of sabo dams is to arrest the frontal wave of debris, store as much solid material as possible and drain the debris flow of the fluid matrix.

Sabo dams are constructed in steep mountain canyons near the source of debris in the upper watershed. The storage capacity of sabo dams is limited by the steep slope, but its purpose is to remove the largest debris elements from the flow matrix. The concrete walls of sabo dams are extremely thick (up to 10 m) and are constructed with drain pipes or steel frame structures (such as railroad rails) to permit drainage of the pore water. Once the pore water is drained, the mobility of coarse clasts decreases very rapidly. The design of sabo dams requires an assessment of the potential storage volume, maximum impact forces, protection against scour, stability under static loading, and a plan for maintenance access and debris removal. Sabo dams in basins generating frequent debris flows should be periodically inspected for impact damage, foundation stability and scour around the structure. Some sabo dams have early warning systems to monitoring the debris flow arrival or the rates of filling to provide advanced warning for downfan evacuation.

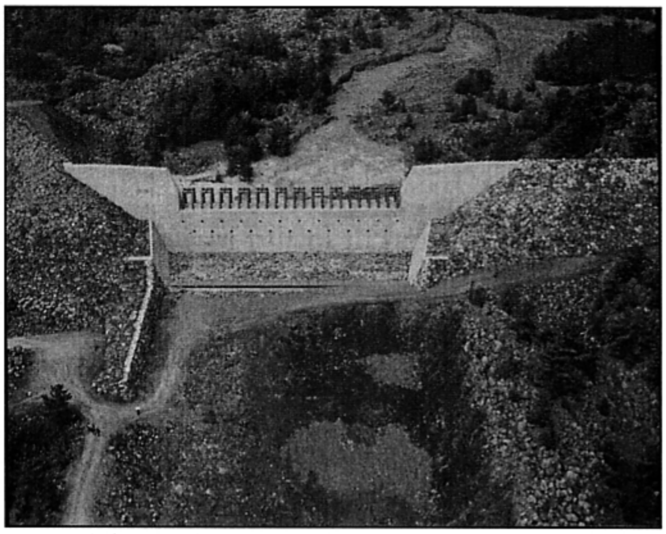

Figure 9. Example of Sabo dam

Other recommended measures to mitigate the damage of debris flows are limited to detention basins. Channel conveyance off the alluvial fan is not suggested because a break-in-slope or channel transition can cause the debris flow to abruptly stop and plug the conveyance facility. Debris flows generally will not flow on the mild slopes of alluvial fans and tend to pile up near fan apex. In most cases, debris flow hazard avoidance is the preferred mitigation.

In summary, most effective countermeasures for debris flows are: 1) sabo dams to retain the clasts in the upper part of the watershed and 2) conveyance channels to drain the turbulent fluid matrix.

The Disaster Prevention Research Institute of Kyoto University, et al. (1999), developed a detailed review of the countermeasures against different types of hyperconcentrated flows in the city of Dongchuan, China, including types of structures and problems encountered throughout the years.

CONCLUSIONS

The rheology of hyperconcentrated sediment flow is relatively complex. The quadratic formulation describes the continuum of flow behavior ranging from mud floods to debris flows. The quadratic rheological model combines the effects of yield, viscous, turbulent and dispersive stresses in hyperconcentrated sediment flows. Mudfloods are turbulent flows with large concentrations of non-conhesive sediment. Mudflows carry large concentrations of fine and cohesive sediment and are characterized by high viscosity. Yield and viscous stresses are dominant. Debris flows contain large concentration of gravels, cobbles and boulders and are characterized by dominant dispersive stress. Numerical modeling of mud floods, mudflows and debris flows is possible with the two-dimensional model FLO-2D.

This paper emphasizes the need to design appropriate mitigation structures based on the rheological behavior of hyperconcentrated sediment flows. Straight, uniform flowing channels that convey the water and sediment off alluvial fans are best suited for mud floods. Detention basins, deflection walls, berms and levees are best suited for mudflows. Thick sabo dams in steep mountain canyons are recommended to arrest debris flows, with appropriate drainage of the fluid matrix.

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