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MODELING OF DEBRIS FLOWS

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PREFACE

Debris flow is a rapid flow of debris with sufficient water to disperse grains uniformly throughout the whole depth. Occurrence of debris flows is a common natural phenomenon. Dam break flows, land slides, flows in a mountainous terrain are some of the examples. It is associated with high erosion resulting in loss of life and property. Thus, a systematic study by modeling of this flow is important to analyze the phenomenon and for a successful disaster management scheme associated with this. Though it is a sort of open channel flow, the wide range of variations in the particle size distribution and their concentrations make it different. The Newtonian fluid approach is no more valid as the flowing debris is a non-homogeneous and non-Newtonian fluid. The rheological properties of the debris are different. Therefore, estimation of the bed friction will be different unlike the case of ordinary open channel flows for which empirical relations (Manning formula, Chezy formula, Darcy-Weisbach formula) for bed friction are available. Two main characteristics of debris flow are high velocity and presence of a wave front. Analysis of debris flows can be performed by experimental modeling and/or mathematical modeling. However, the rheological characteristics can only be found out by laboratory measurements. Some key issues in debris flow study are quality and quantity of data, categorization of debris flow, field measurements of flow and evaluation of unsteady bed friction.

This report entitled '*Modeling of debris flows*' presents the relevant literature survey in the topic. It will be helpful in actually modeling debris flow. This is part of the regular work programme of the flood studies division of the institute. The study has been carried out by Dr. P. K. Mohapatra, Scientist 'B'.

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ABSTRACT

Literature review on modeling of debris flow is presented in this technical report. Debris flow is a common natural phenomenon. It is associated with high erosion capacity. Modeling of such flow is necessary from engineering point of view. The main difference from other open channel flows is two-fold, (1) flow material is different and (2) flow characteristics are different. Experimental methods are necessary to measure rheological properties and to validate a numerical model. Field measurements of debris flows are difficult. Equations governing the flow are well known. Relation for bed friction is not understood properly. It is estimated based on rheological properties of the flowing debris. In the numerical treatment of debris flow, evaluation of bed friction is important. Other features in the numerical modeling are; Error analysis, Validation, Capturing the shock etc. Use of DAMBRK, the popular model for dam break studies, for modeling debris flow is also presented.

1.0 INTRODUCTION

Debris flow is a form of rapid mass movement of a body of granular solids, water, and air, with flow properties varying with water and clay content, sediment size and sorting (Phillips and Davies 1989). It is a sort of massive sub-aerial sediment motion. A massive sediment motion is the falling, sliding, or flowing of conglomerate or the dispersion of sediment, in which all particles as well as the interstitial fluid are moved by gravity. The relative velocity between the solid phase and fluid in the direction of displacement of mass plays only a minor role in this type of flows. On the other hand, lift and drag forces due to relative velocity are essential for individual particle transport in ordinary fluid flow. Sometimes debris flow, in literature, is also referred to as *mud flow*. Debris flow is a special case of open channel flow where the flow material is not homogeneous. It very often moves with a high speed, and therefore, has very strong destructive power. Analysis of this flow is very important from engineering point of view, because, it is always associated with enormous loss to life and property. Establishment of the countermeasures to prevent the disaster due to the debris flow needs the knowledge of the behavior of such kind of hyper-concentrated flows, not only its occurrence, but also its mechanism and its instability (Legono and Jain 1989).

Natural occurrence of these flows is very common. Land slides, dam-break flows, lava flows, and flows in mountainous channels are some examples. Debris flow may also take place due to human activities e.g. disposal of sediments from reservoirs and flows from ash ponds in thermal power plants. The initiation of debris flow has been attributed to the following causes. Under some conditions, a landslide turns into debris flow. A naturally built dam that checks a gully may collapse into debris flow. With the appearance of a surface water stream in heavy rainfall, an accumulation of debris may become unstable and turn into a debris flow. Dam break debris flows may cause loss of life and severe destruction of property in the downstream reach of a debris reservoir. For example, the initial tailings dam of the Jinshan debris reservoir in Anhui, China broke in the early morning of April 30, 1986, resulting in a high speed debris flow downstream from the initial tailings dam. The total discharge of the debris and water mixture was estimated to be about 800, 000 m^3. The debris flow quickly engulfed a downstream village. Debris flow is an inevitable part in all earthen dam failures. Sakurajima is a strato-volcano standing at the center of the Kagoshima Bay, Japan. The hill slopes are susceptible to erosion, slope sliding and occurrence of debris flow. In Sakurajima volcano, debris flows have occurred frequently during rains and created serious damages to the foot areas.

Debris flows may be divided into four categories based on the mechanism of motion, properties of interstitial fluid, velocity of displacement, and travel distance (Takahashi 1981). These are; (a) *fall, landslide, creep*, in which all individual particles move downward with little internal deformation, (b) *sturzstorm*, for catastrophic landslides, in which disintegration occurs in the initial stage of movement and the debris flows along a nearly horizontal valley floor with tremendous speed, (c) *pyroclastic flow*, a very rapid flow of a mixture of hot ash and gas ejected explosively from a volcanic crater, in which the sediment could be supported by the upward flow of fluid due to the rapid expansion of in-folded air or emitted gas, (d) *debris flow* in which the grains are dispersed in water or clay slurry.

There are several aspects of debris flow modeling. The prediction of the hazards to be expected from debris flows must be based on empirical field data. There could be a severe shortage of data. Therefore, it is a matter of urgency that efforts be made to improve the quality and quantity of the data available. It is found by Takahashi (1978) that once the debris flow starts to occur, the process of picking up material from the bed would last continuously, the driving force increases as well as the discharge of water sediment mixture. The only possible cause for the flow to decelerate is the increase in resisting shear to exceed the driving force by mean flatter slope, or coarser grains or smaller rate of water flow. It has been known for many years that most debris flows move down-slope as a fluid rather than as a sliding solid. Characteristics of debris flows demands special attention and plays an important role in its analysis. Debris flows differ from other natural unconfined flows (Laigle and Coussot, 1997) in two main respects: (1) The nature of the flowing material, constituted by a mixture of water, clay and granular materials, and (2) the nature of the flow itself, which is rapid, transient, and includes a steep front mainly constituted of boulders. Flow materials are not homogeneous. The particle sizes may vary from fine silts to big boulders. The concentration of each material is also different. Thus, the rheological property of the flow material varies over a wide range, and is often the governing criteria for the flow analysis. As a first approximation, fluctuations in the concentration are neglected and the fluid can be considered homogeneous, in a macroscopic scale. Considering the flow characteristics, it is generally transient, three-dimensional and shocks/bores are very often present. The wide variation in particle sizes and their concentrations makes it difficult to define debris flow with a single constitutive law (Mainali and Rajaratnam, 1994). Front of the debris flow swells and brings together the larger boulders. The rear part contains more water, and grain sizes in this part are smaller than in the front. The velocity of the debris flow varies between 0.5 to 20 m/s. The gradient of the gully at this point is of the order of 200. Densities vary from 1400 kg/m^3 to 2530 kg/m^3. The volume concentration ranges from 25% to 80%. A debris flow exerts enormous impact forces on obstacles in its way. However, after the flow issues from the canyon and spreads out upon the plain, its power is quickly lost. It is common that a house is buried to the eaves by debris without serious damage. This probably suggests that the flow is very thin and slow at the time of the stoppage. The erosion capacity of the debris flow in the source area is severe. However, fully freighted debris flow has little erosive effect, and one can sometimes see that the paving of roads has not been damaged on passage of the flow. The data so far reveal that debris flows occur on sediment beds in mountain canyons whose slopes are steeper than 150, and they come to rest on plains or in canyons whose slopes are steeper than 30. Finer particles, however, may be transported to flatter places as bed load and suspended load by the surface stream squeezed out by the deposition of debris.

Modeling of debris flows can be performed by either physical modeling or by mathematical modeling. In a physical model, measurements for the rhelogical properties (stress - rate of strain relationship) and flow parameters (velocity, flow depth etc.) are done. Due to very high velocity of debris flow, it is difficult to measure the flow parameters in field. In case of mathematical models, analytical and/or numerical methods are employed. Shallow water equations or derived expressions (e.g. kinematic wave approximation) are generally used for debris flow modeling. However, computation of bed friction in the momentum equation for debris flows is different from that of ordinary open channel flows where well- known relations are available. The main point of concern between various numerical models is the treatment of the bed friction. The formulation for the bed friction depends on the rheological assumptions. Muddy debris flows are generally, sufficiently viscous to flow in laminar regime (Hunt 1994). Coussot (1994) established a theoretical link between real muddy debris flows and a Herschel-Bulkley model fluid by using similarity analysis. He also derived a mathematical expression due to bed friction in laboratory flumes with steady and uniform flows. The front of debris flows is generally made of boulders and the clay fraction is very low. Therefore, the front cannot be represented by a Herschel-Bulkley model as its nature is granular.

Regarding the mechanism of debris flow, the occurrence and behavior of pulsing debris flows result from the presence of high concentration of coarse grains shearing in a dense and viscous slurry of fine grains in water. The occurrence of macro-viscous grain shearing conditions is associated with the onset of the main features of debris flows. The instability of macro-viscous flows causes the flow to break up into a series of pulses or waves. This process is assisted by the tendency of the coarse grains to jam at high concentrations.

Objectives

The main objectives of the present technical report is to present the literature review on debris flow modeling. The sections presented include the equations governing debris flow, the rheological models to model such flows and finally the numerical modeling for a detailed analysis of the flow. In the appendix, use of DAMBRK program to model debris flow is presented. The effects of non-homogeneity, i.e. variation of concentration in space, are beyond the scope of this technical report.

2.0 GOVERNING EQUATIONS

The equations governing the debris flow are presented in this section. As stated earlier, debris flow is a case of open channel flow and self-weight or gravity is prime motivating force. Therefore, the governing equations are same as those for open channel flows. These equations are for conservation of mass and momentum. An equation for energy conservation is not *generally* used. The equations presented are in increasing order of simplifications. Successful analysis of the debris flow often depends upon the accuracy of the governing equations used in the formulation.

2.1 Navier-Stokes Equations

Navier-Stokes equations represent the complete description of fluid flow at any Reynolds number. The three-dimensional equations for a viscous fluid are;

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Momentum equation in x - direction:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+g_x+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

Momentum equation in y - direction:

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial vw}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+g_y+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

Momentum equation in z - direction:

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial w^2}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+g_z+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

In the above equations (Eqs. 1-4), t is the time, and x, y, and z are coordinate axes along longitudinal, transverse and vertical directions, respectively. u, v, w are the three velocity components in x, y, z directions; P is the pressure; g is acceleration due to gravity; ν is the kinematic viscosity of the fluid; and, ρ is the density of the fluid. In tensor notation these equations can be written as

Continuity equation:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{5}$$

Momentum equation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P^*}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} \tag{6}$$

These equations are very difficult to solve even with the advanced numerical techniques and very fast computers. Because, the length scales vary over a wide range due to turbulence and enormous computer space and time is necessary. However, *direct numerical simulations* (DNS) can be performed with the help of a super computer to capture these detailed turbulence characteristics.

2.2 Reynolds Equations

As Navier-Stokes equations are difficult to solve, Reynolds equations are generally attempted to analyze the flow. The velocity and pressure are divided into the average and fluctuating parts. Thus, the following equations are substituted

$$U_i = \overline{U}_i + u_i'$$

$$P = \overline{P} + P'$$

in Eqs. 5-6 to obtain the Reynolds averaged equations. Reynolds equations are;

Continuity equation:

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0 \tag{7}$$

Momentum equation:

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}^*}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) - \overline{u_i' u_j'}\right] \tag{8}$$

In the above equations, the variables with over-bars are the averaged quantities and those with prime signs are their respective fluctuations. When compared to Eq. 6, the last term in Eq. 8 is the additional term and is known as Reynolds stresses. Evaluation of these terms is known as *turbulence modeling* (TM). There are a number of turbulence models available in literature (ASCE, 1988). Both DNS and TM are out of the scope of this review report. Modeling of debris flow can be done by numerical solution of Eqs. 7-8. Unlike the case of water where ρ and ν are well known, the characteristics of the flowing debris, based on laboratory measurements, should be used.

2.3 Two-dimensional Saint -Venant Equations

In the analysis of open channel flows, it is traditional to use shallow water theory. In shallow water theory, it is assumed that the velocity is uniform in a vertical plane. This assumption results in a hydrostatic pressure distribution along the depth. Using this assumption and integrating over depth, the three-dimensional Navier-Stokes equations can be simplified to two-dimensional Saint-Venant equations.

Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \qquad (9)$$

Momentum equation in x-direction:

$$\frac{\partial uh}{\partial t}+\frac{\partial}{\partial x}\left(u^2h+\frac{1}{2}gh^2\right)+\frac{\partial}{\partial y}\left(v^2h\right)=gh\left(S_{ox}-S_{fx}\right) \qquad (10)$$

Momentum equation in y- direction:

$$\frac{\partial vh}{\partial t}+\frac{\partial}{\partial x}\left(u^2h\right)+\frac{\partial}{\partial y}\left(v^2h+\frac{1}{2}gh^2\right)=gh\left(S_{oy}-S_{fy}\right) \qquad (11)$$

In the above equations (Eqs. 9-11), u and v are depth-averaged velocities along x and y directions, respectively. S_0 is the bed slope and S_f is the friction slope. Computation of friction slope in case of open channel flows with water as the flowing material is done by using empirical formulae such as Chezy equation, Manning equation or Darcy-Weisbach friction formula. However, in case of debris flow, the flow material is no more homogeneous and Newtonian fluid. Therefore, based on the rheological properties (stress-strain relationship) of the flow material, the friction slope is evaluated. A detailed procedure to estimate the friction slope for debris flow is described else where in this report. Here, it is worth mentioning that the actual rheological parameters of the debris flow can only be evaluated by laboratory measurements.

2.4 One-dimensional Saint-Venant Equations

Further simplification to the equations presented in the above section can be made. The flow variables can be assumed to have negligible variations along the transverse direction (In many cases this is not true.). Thus, neglecting the variations along y-direction, Eqs. 9-11 can be written in one-dimensional form.

Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}=0 \qquad (12)$$

Momentum equation:

$$\frac{\partial uh}{\partial t}+\frac{\partial}{\partial x}\left(u^2 h+\frac{1}{2}gh^2\right)=gh\left(S_o-S_f\right) \qquad (13)$$

Before closing this section, it may be mentioned that the equations presented in the above paragraphs are termed as dynamic equations. There are cases of studies using simplified forms of equations. Thus, though it is possible to use a different formulation (eg. Kinematic wave equation, diffusion wave equation) it is suggested that one-dimensional Saint-Venant equations or equations of higher accuracy should be used in debris flow modeling.

3.0 EXPERIMENTAL MODELING

Modeling of debris flows by experimental studies is a necessity. As stated earlier, there are two aspects of a debris flow i.e. flow material and flow parameters. Rheological characteristics of the flowing debris can only be achieved through physical measurements. These properties are used in the numerical models for estimating the bed friction. Results obtained from experimental studies are used to validate the numerical models. As classification of debris flow is not easy, detailed experimental studies can help to find out the category of the debris flow under study. However, measurements of a debris flow are not easy. Due to high speed of the flow and presence of materials like boulders, special methods are used. In the following paragraphs, both aspects of experimental modeling (i.e. rheological properties of the flowing debris and flow parameters) are described.

3.1 Rheological Modeling

Modeling debris flows requires a rheological model for sediment-water mixtures (Chen 1988). Various models relating stress, strain, and time are available in literature. Highly theoretical models are too complicated to be useful in practice. On the other hand, simpler semi-empirical models are limited to a narrow range of applications for lack of adaptability. Thus, the selection of a proper rheological model is a major issue in the analysis of debris flows.

Unlike solids which have definite relationship between shear stress and shear strain, fluids posses a relationship between the shear stress and rate of shear strain. This relationship is known as the rheological behaviors of the fluid and classification of fluids can be done based on this property. A general equation showing the rheological behavior may be of the following form.

$$\tau = \tau_c + \mu\left(\frac{du}{dz}\right)^r \qquad (14)$$

In the above equation, τ is the shear stress, τ_c is the critical shear stress, μ is the dynamic viscosity, du/dz is the rate of strain (velocity gradient) and r is the rheological exponent. The shape of the curve (convex upward, convex downward, straight line etc.) indicating the rheological behavior, depends on the values of τ_c and r. For example, in case of Newtonian fluids (such as water), $\tau_c = 0$ and $r = 1$, and the curve is a straight line and passes through the origin. However, for debris flows, no definite values for the above parameters are assigned. Because, the particle size distribution ranges from silt to boulders and their concentration may also vary over a wide range of values. In absence of definite classification of debris flows, different rheological models are assumed. Based on the rheological properties, debris flows can be broadly divided into three categories (Table 1). The behavior of debris flows for a given concentration changes mostly with their clay fraction (Clay: Particle sizes ≤40 μm). For a very low clay fraction, granular interaction is predominant and for a higher clay fraction viscoplastic behavior. These models are with the limitations associated with them. Therefore, applicability of a specific rheological model to analyze a debris flow should be thoroughly examined before applying to a case study.

Table 1: Classification of debris/mud flows based on rheological properties

Rheological property	Example	Application
Yield-stress viscoplastic	Bingham model	Viscous debris flows, muddy debris flows
Granular fluid model	Bagnold model	Granular debris flows
Combination of different dissipations	Turbulence and Newtonian behavior	Low viscosity debris flows

3.1.1 Bingham Plastic Equation

In the Bingham plastic equation, the shear stress depends linearly on the rate of strain, i.e. $r = 1$ in Eq. 14. This is suitable for debris flows of high viscosity cohesive materials. It can also be used for clay and silt slurry in the presence of some sand size particles under low shear rates. Eq. 14 can be integrated through depth and assuming a linear shear

$$\frac{u}{u_m} = \frac{1-\left[1-\frac{y}{h}\left(\frac{h}{h_0}\right)\right]^2}{1-\frac{1}{3}\left(\frac{h}{h_0}\right)} \qquad (15)$$

profile to get the velocity distribution.

Eq. 15 is valid for $0 \leq y/h \leq h_0/h$. In this equation, u is the velocity at a distance y from the bed, u_m is the channel mean velocity, h is the depth of flow and h_0 is the height above bed where $\tau = \tau_c$.

3.1.2 Bagnold's Model

Besides the above theory, there are theories of modeling granular flows that use the rheological approach with plastic and viscous components. Bagnold used N, a ratio of the apparent viscosity in the grain inertia regime to that in the macroviscous regime as

$$N = \frac{\lambda^{0.5}\rho_s D^2}{\mu}\frac{du}{dz} \qquad (16)$$

where D = the particle diameter; μ = the dynamic viscosity of the interstitial fluid; and ρ_s = the density of the particle. The linear concentration λ is related to the volumetric concentration (C_v) and maximum packing (C_*) by

$$\lambda = \left[\left(\frac{C_*}{C_v}\right)^{1/3} - 1\right]^{-1} \tag{17}$$

This dimensionless number N is used to distinguish between grain inertia regime where $N>450$ and a viscous regime where $N < 40$.

In the grain inertia regime, the grain shear stress τ_g and the normal shear stress P, can be written as

$$\tau_g = P \tan \rho_d \tag{18}$$

such that

$$P = a_i \lambda^2 \rho_s D^2 \left(\frac{du}{dz}\right)^2 \cos\phi_d \tag{19}$$

where, a_i = an empirical constant; and ϕ_d = the dynamic angle of friction. Despite several limitations, Bagnolds model paved the way for granular flow research. Takahashi (1978) integrated Eq. 18 for a steady flow in a channel to give

$$\frac{u}{u_m} = \frac{5}{3}\left[1 - \left(1 - \frac{y}{h}\right)^{3/2}\right] \tag{20}$$

3.1.3 Takahashi's Model

For the case of highly sediment-laden flow, the particles are sufficiently small to be suspended by turbulence in water. A turbulent shear stress τ_t (analogous to the pure-water turbulent stress) to the grain shear stress to give the total shear stress

$$\tau = \tau_t + \tau_g \tag{21}$$

where τ_t is given as

$$\tau_t = -\rho_m \overline{u'v'} = \rho_m l_m^2 \left|\frac{du}{dz}\right| \frac{du}{dz} \quad (22)$$

The mixture density $\rho_m = \rho_f + C_v(\rho_s - \rho_f)$, where ρ_f is the density of the fluid, lm is the mixing length and u', v' are the fluctuating velocities. Assuming a linear shear stress and $l_m = \kappa y$, where κ is the Karman constant, the velocity in the channel is given by

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y + \sqrt{y^2 + \phi^2}}{y_0 + \sqrt{y_0^2 + \phi^2}} \quad (23)$$

where, for a rough bed, $y_0 = k_s/30$, $u_* = (gh \sin\theta)^{0.5}$, and

$\phi^2 = \lambda^2 (a_i \sin\phi_d / \kappa^2)(\rho_s/\rho_s) D^2$

k_s is the equivalent sand grain roughness of the bed, and θ is the bed slope.

3.2 Velocity and concentration measurements

Velocity and concentration distributions have been more difficult to measure than the rheological properties. This is because of the highly abrasive nature of the debris flows. It is not possible to use the probes generally used in open channel flows. The few measurements that have been made are sketchy and of short duration. As reported by Mainali and Rajaratnam (1994), Yano and Daido (1965) measured the velocity distribution in a clay slurry ($C_v < 13$ %), using a modified pitot tube, and showed that the slurry behaved as a Bingham fluid. The dynamic and static pressures needed to inject water into the flow to prevent clogging of the tube gave the flow velocity. Wang(1990) used a similar method combined with tracer particles to measure velocity profiles and radio isotopes to measure concentration profiles. Takahashi(1978) made velocity and concentration measurements in a channel inclined at 100 - 200 for flows having 33% - 44% sediment by weight. Flows were generated by passing a constant discharge over a saturated mass, which subsequently failed and flowed in a quasi-steady manner. Velocity was measured using close-up photographs of particle movement in contact with the wall. Hirano and Iwamoto (1981) measured velocity and concentration profiles in a bore using video camera. The concentration was determined by counting particles in contact with the wall. The velocity distribution appeared to be almost uniform and the concentration was found to be smaller near bed. An optical sensor method has been tried for dry granular flows (Savage 1979). In this technique, two optical sensors are arranged side by side next to a transparent wall. A cross correlation of the output of the two sensors gave the velocity of the particle. This, however, has the same limitations as the photographic technique. Winterwerp et al. (1990) used an electromagnetic flow meter for their measurement of velocity and a conductivity probe for measurement of sand concentration. Mainali and Rajaratnam (1994) used a specially designed volumetric flow sampler to measure the vertical velocity and concentration profiles at the center of the channel. The flow was uniform and of high concentration sand-water mixture. The flume was set on a slope of 28.6%.

4.0 NUMERICAL MODELING

Although modeling of debris flow can be achieved by experimental studies, it is convenient to use a mathematical model. Experimental models are time consuming and costly. Besides, scale effects are also present. The measurements are to be carefully taken for accuracy. However, mathematical modeling can be successfully studied to analyze debris flow. It should be borne in mind that experimental models cannot be replaced by mathematical models, because, experimental models add to the basic understanding of the flow phenomenon. A mathematical model also has to be validated against some measurements. Simulation of complicated geometry is also a difficulty. However, due to the efficiency in time consumed and effective reduction in cost, generally, a mathematical model is used. A mathematical model can be analytical or numerical. In an analytical model, many assumptions are made to simplify the flow so that the equations become simpler. For example flow can be assumed to be steady and expression for velocity distributions can be obtained (see previous section). An analytical solution, however, depends on the basic rheological relation on which it is based. Analytical solutions for steady uniform debris flows in wide channels obtained by Chen (1988) are considered as a bench mark in the area of debris flow analysis. These solutions are based on a generalized viscoplastic fluid and Bagnold's simplified assumption of constant grain concentration.

After the advent of fast computers and efficient numerical methods, numerical modeling has become very popular. A debris flow can be successfully analyzed using a numerical model. The performance of a numerical model depends upon the selection of governing equations, numerical scheme to be used and the evaluation of the bed friction. In the following sub-sections, numerical modeling of debris flow is presented.

4.1 Governing Equations

The governing equations in different degree of accuracy are presented in Section 2. These equations are non-linear partial differential equations. Generalized analytical solutions are not available. Therefore, these equations are to be solved numerically. Before attempting solving the equations, proper selection of the equations are to be done. In literature, one- and two-dimensional Saint-Venant equations are successfully used to simulate debris flows. However, solution of Reynolds averaged equations provide more accurate solutions. Solving of these equations is known as Turbulence modeling. Different turbulent models are available in literature for water flows and various model parameters are well established. However, for debris flows, these parameters need further studies. In the following sections, the discussion presented is limited to numerical solution of Saint-Venant equations.

4.2 Numerical Solution

The governing equations (Saint-Venant Equations) are non-linear hyperbolic partial differential equations. These are to be solved numerically. There are different methods available in literature. The methods that find wide application are;

1. Method of Characteristics (MOC)
2. Finite-Difference Method (FDM)
3. Finite-Element Method (FEM)
4. Finite-Volume Method (FVM)
5. Spectral Method (SM)

For open channel flows, FDM is well tested and is used successfully in many studies. FDM may be explicit finite-difference or implicit finite-difference. The partial differential equations are converted to equivalent algebraic equations by applying the principle of finite-difference. However, things like error analysis and validation constitute important limbs in any numerical method. Here, it should be mentioned that all debris flow are associated with high speed and presence of a bore. Therefore, the numerical method to be used should be able to simulate these characteristics of debris flow.

4.2.1 Solution Strategy

The solution strategy for numerical modeling of debris flow is presented in Fig. 1. Individual components are discussed in the following paragraphs.

INPUT: The input values to the numerical method are;
Channel geometry including cross section and bed slope, acceleration due to gravity, rheological parameters of the flowing debris, initial flow parameters, the flow discharge hydrograph at the upstream, the spatial step sizes, final time of computation, any criteria for stability such as Courant number.

INITIAL CONDITIONS: The flow variables (all velocities and flow depths) are to be prescribed for all computational nodes. These values refer to the condition prior to the computation.

STABILITY: A stability condition is to be used. Knowing the spatial step size, the time step size is computed. This ensures that the total error does not increase as time progresses. Theoretically, implicit schemes should require no stability criteria as they are unconditionally stable. However, previous studies show that when the stability criteria is used in implicit schemes their performance in terms of accuracy (not efficiency) increases. A popular stability condition used in hyperbolic equations is the Courant-Frederich-Lewis condition given by

$$\Delta t = \min\left[\left(CFL\frac{\Delta x}{\max(u+c)}\right),\left(CFL\frac{\Delta y}{\max(v+c)}\right)\right] \tag{24}$$

BED FRICTION: Unlike in the ordinary open channel flows where the bed friction is estimated using empirical relations such as Manning equation or Chezy equation, a different relation based on the rheological characteristics of the debris flow is used. One such relation as given by Laigle and Coussot (1997) is described below.

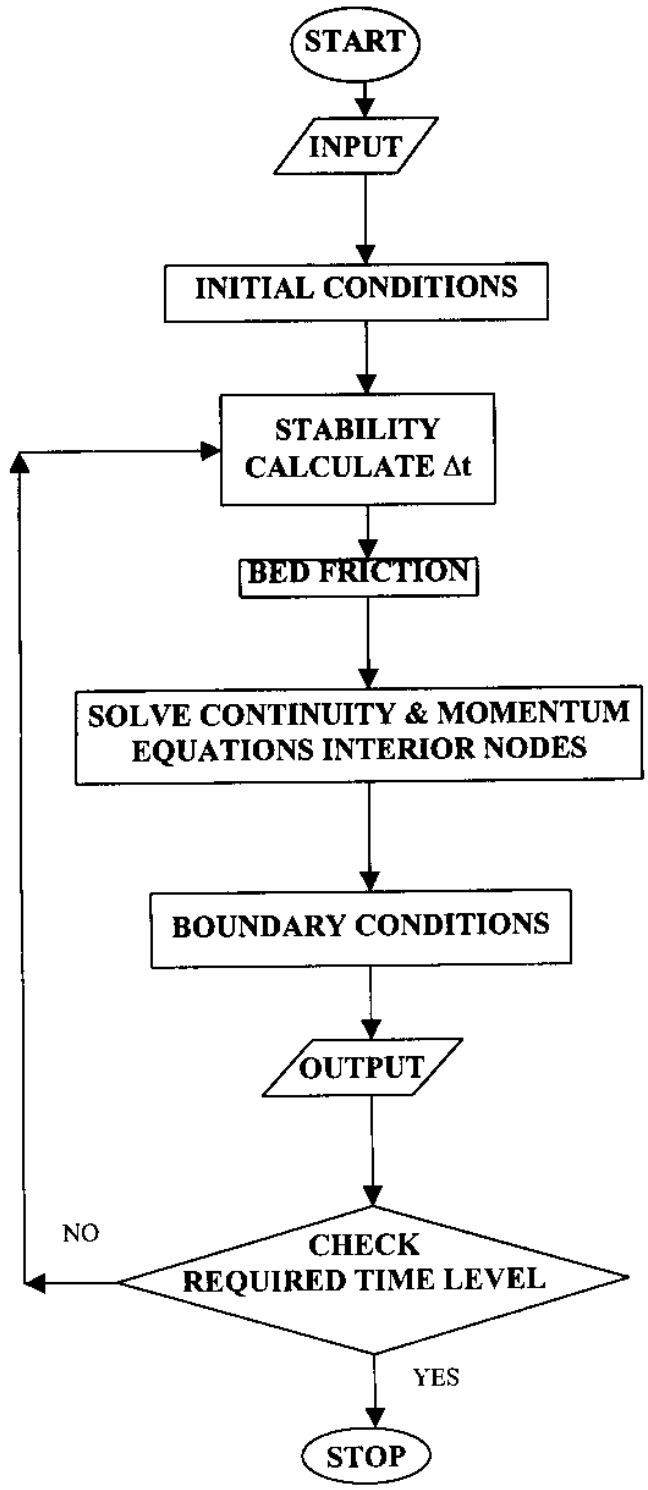

Fig. 1 Flow chart showing solution strategy for numerical modeling of debris flows

The friction slope (the term S_f as used in Eqs. 10, 11 or 13) is to be estimated using

$$S_f = \frac{\tau_p P}{\rho g h} \qquad (25)$$

where, P is the wetted perimeter, ρ is the density of the flowing debris, g is acceleration due to gravity and h is the flow depth. τ_p is evaluated by

$$\tau_p = \tau_c\left[1 + a(H_b)^{-0.9}\right] \qquad (26)$$

τ_c is the critical shear stress as given in Eq. 14 and a is a constant and it depends on the cross section.

$a = 1.93$ for wide rectangular channel

$a = 1.93 - 0.43\ tan^{-1}(10h/B)^{20}$ where, B is the width of the channel

H_b is a non-dimensional number and is defined by

$$H_b = \frac{\tau_c}{\mu}\left(\frac{h}{u}\right)^r \qquad (27)$$

In the above equation, τ_c, μ and r are the symbols defined in Eq. 14, h is the flow depth and u is the average flow velocity.

CONTINUITY AND MOMENTUM EQUATIONS: The continuity and the momentum equations are discretized depending on the numerical scheme used. The discretized equations represent the algebraic equivalence of the partial differential equations. These algebraic equations are solved suitably. In case of an implicit procedure, an efficient matrix solver should be used.

BOUNDARY CONDITIONS: The continuity and the momentum equations are solved for interior computational nodes only. Therefore, the flow variables are to be estimated for the boundary nodes by imposing the boundary conditions. The general procedure is that the time history of the discharge (hydrograph) at the upstream end and the stage discharge relation at the downstream end are prescribed. Additional information using extrapolation may be used at the boundaries.

The procedure is repeated until the required time level is obtained.

4.2.2 Error Analysis

The results should be checked for error analysis. The basic test that should be performed is verifying the results for grid convergence test. The results should give convergent results as the grid size is made finer and finer. In addition, the sensitivity of the results for various parameters used should also be studied. For example, the effect of Courant number and rheological exponent should be studied.

4.2.3 Validation

The results obtained from the numerical solution should be validated against some measured values as there are many uncertainties associated with a numerical formulation and mathematical equations are always inadequate to represent a natural phenomenon. Besides, validation helps in building confidence in the numerical scheme.

4.2.4 Limitations

The limitations in a numerical scheme arise out of the assumptions used in the governing equations and accuracy of the used numerical method. Therefore, in analyzing the results obtained from a numerical study the limitations associated with this should be borne in mind.

4.3 Shock Absorbing Schemes

As already stated debris flow is always associated with the presence of a bore, therefore, numerical scheme used to analyze debris flow should have shock capturing capabilities. The bore is like a singularity. Mathematically, the function is discontinuous at the bore. Schemes like Lax diffusive scheme and MacCormack scheme do not capture the shock automatically. Therefore, essentially non-oscillating (ENO) scheme or total variation diminishing (TVD) scheme should be used. Ordinary methods using the concept of artificial viscosity may also be used. These schemes reduce the high oscillations present near the shock front.

CONCLUSION

In this report, modeling of debris flow was presented. Occurrence, effects and importance of debris flow were described. Special characteristics of debris flow that make it different from other open channel flows were discussed. Various issues in the modeling of debris flows were also presented. Experimental models to study the rheological characteristics were mentioned. Difficulties in field measurements of debris flows were pointed out. Mathematical models for analyzing debris flows were found to be convenient. Governing equations were same as those used in open channel flows. However, estimation of bed friction was different. It was governed by the rheological characteristics of the debris. In addition, also discussed are different aspects of numerical modeling. In the appendix use of DAMBRK for debris flow study was presented.

The following study in future may be useful.

1. Numerical modeling of debris flow using two-dimensional Saint-Venant equations.
2. Observed data for a case study in India (for validating the numerical model).
3. Computations using DAMBRK.
4. Sensitivity analysis of rheological parameters.

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APPENDIX

Use of DAMBRK for debris flow modeling

The DAMBRK model may be used to route specified hydrographs of debris flows. The momentum equation used for routing is

$$\frac{\partial s_m Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right) + gA\left(\frac{\partial h}{\partial x} + S_f + S_e + S_i\right) + L' = 0 \qquad (A-1)$$

In the above equation (Eq. A-1), x is the longitudinal distance along channel, t is the time, s_m is the sinuosity factor, Q is the discharge, β is the momentum correction factor, A is the active cross section area, g is acceleration due to gravity, S_f is the boundary friction slope, S_e is the expansion-contraction slope, S_i is the additional friction slope associated with internal viscous dissipation of non-Newtonian fluid such as debris flows and L' is the momentum effect of lateral flow.

The viscous dissipation term S_i in the above equation is determined by using

$$S_i = \frac{\kappa}{\gamma}\left[\frac{(b+2)Q}{AD^{b+1}} + \frac{(b+2)(\tau_0/\kappa)^b}{2D^b}\right]^{\frac{1}{b}} \qquad (A-2)$$

in which γ is the unit weight of the fluid, τ_0 is the yield strength of the fluid, D is the hydraulic depth, $b=1/m$ where m is the exponent that fits the stress vs. rate of strain relationship of the fluid, and κ is the apparent viscosity or scale factor of the power function.

A control parameter *MUD* is used to activate the capability of the program to simulate debris flows. The parameters κ, τ_0, and m are given as input. The debris flow capability within the DAMBRK program is controlled by the parameter *MUD*, which allows the selection of the following solution methodologies:

(1) if *MUD = 0*, no debris flow capabilities are used and S_i is set to zero in Eq. A-1;

(2) if *MUD = 1*, the specified debris flow hydrograph is routed through a very steep channel reach via a nonlinear iterative Muskingum-Cunge algorithm;

(3)if *MUD* = *2*, the Muskingum-Cunge method is used for a very steep reach or channel and the routed hydrograph is then again routed through a moderate to flat reach of channel using Eq. A-1;

(4) if *MUD* = *3*, the specific debris flow is routed through the channel routing reach using Eq. A-1, and

(5) if *MUD* = *4*, the specified hydrograph routed through two reaches as in *MUD* = *2* except Eq. A-1 is used for both the cases.

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