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ANALYSIS OF DIFFERENT MODELS TO PREDICT THE MEAN FLOW VELOCITY IN HYPERCONCENTRATIONS, MUDFLOWS AND DEBRIS FLOWS

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ABSTRACT

Design of man-made channels or improvement of natural rivers to convey hyperconcentrations, mudflows and debris flows has been studied in the past but only recently has it acquired an importance of its own. In terms of sediment engineering, the problem becomes the determination of mean flow velocity of the hyperconcentrations to estimate the capacity of natural or man-made channels. Many investigators have attempted to predict the mean flow velocity of hyperconcentrations based on hydraulic parameters of the channel and characteristics of the sediments, including Jaeggi (1983), Takahashi (1978) and Julien (1993). This paper evaluates the models developed by those investigators by comparing the measured and computed mean velocities. For this purpose, an extensive data of measured mean velocities (field and laboratory) is compiled and a database is set up.

The Jaeggi Model is a turbulent model and includes the resistance to flow in terms of turbulent stress only. It should be noted that the factor $Exp(\alpha_1 h/d_{90} S_o^{0.5})$ in the Jaeggi's original model always turns out to be greater than 1 when calculated against the whole field and laboratory datasets. It is, therefore, not possible to take the square root of the whole expression $[1- Exp(\alpha_1 h/d_{90} S_o^{0.5})]$ in the Jaeggi's original model. Therefore, the Jaeggi's original model is modified by assuming the factor $Exp(\alpha_1 h/d_{90} S_o^{0.5})$ in Equation (3.0) to be equal to zero for this study and referred as The Modified Jaeggi Model throughout this paper. The Modified Jaeggi Model describes a logarithmic relationship between the resistance to flow and relative submergence h/d_s.

A theoretical model proposed by Julien (1993) is also analyzed in detail. The Julien model includes the effect of all four stresses i.e. yield, viscous, turbulent, and dispersive stress. It describes the resistance to flow in terms of Darcy-Weisbach friction factors f_t and f_d for the turbulent and dispersive stresses respectively. A theoretical model presented by Takahashi (1978) to predict the mean flow velocity of a quasi-steadily moving debris flow front on the basis of dispersive stresses between the moving grains is also analyzed in detail. It should be noted that the Takahashi model is applicable to the motion of steady uniform debris flow only.

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The Julien Model (all four stresses) and the Modified Jaeggi Model (turbulent flow) work more promisingly for the field data with 67% and 76% of the predicted velocities fall within ± 50% of the measured flow velocities respectively. However, the Julien Model does not perform that well for the laboratory data with only 25% of the predicted velocities fall within ± 50% of the measured flow velocities. The Modified Jaeggi Model performs reasonably well against the laboratory data with 58% (93% without Rickenmann Dataset A) of the predicted velocities fall within ± 50% of the measured flow velocities. For the Takahashi Model (dispersive flow), zero percentage of the calculated velocities (with Rickenmann dataset A as an exception) fall within ± 50% of the measured flow velocities for both, field and laboratory datasets.

The net conclusion is that the flow velocities in hyperconcentrations, mud and debris flows can be predicted well from turbulent models (modified Jaeggi). This indicates the predominance of turbulent stresses in hyperconcentrations as compared to the dispersive, viscous and yield stresses.

INTRODUCTION

The need to understand and predict the flows that carry large amounts of sediment load has certainly become very important in the world over the past two decades. A better understanding of highly sediment-laden flows is important not only because of the change in physical and dynamic characteristics of the fluid as compared to the clear water flow, but also because that the flows with large sediment concentration have caused extensive damage, with lives and property lost in the process in recent years.

The occurrence of hyperconcentrated flows is very common to many rivers, channels, and streams in different parts of the world. A clear flowing stream which has little or no suspended sediment can easily be converted into a stream that transports more solids than water by a catastrophic disturbance in the watershed. Initiation of the debris, mud, or hyperconcentrated flow usually requires loose rock and soil deposits, steep slope, and free-flowing water from a snow-melt or a rainstorm. As a debris flow initiated by a landslide proceeds down a steep mountain canyon, it scours material from the channel and increases its mass flow. At the entrance of the alluvial fan of gentle ground slope, the debris flow spreads out, reduces momentum and then stops its movement after reaching flatter areas. Sediment segregates and leaves mud-flood or clear water flowing downstream. Debris flows are also commonly associated with volcanic eruptions when snow, glacial ice, or a crater lake is in proximity to the eruption source (Jan and Shen, 1993).

The occurrence of hyperconcentrations is rather unpredictable and very destructive. On November 13, 1985 catastrophic mudflows swept down the slopes of the erupting Nevado del Ruiz volcano in Colombia, South America, thus destroying structures on their way. Estimates of the death toll ranged as high as twenty-four thousand residents (Mileti, Bolton, and others; 1985). A very serious and destructive eruption of Mount St. Helens took place on May 18, 1980. During the eruption, a debris avalanche deposited some 3 billion cubic yards of rocks, ice and other material in the upper 17 miles of the North Fork Toutle River valley. Mudflows triggered by the eruption carried large volumes of sediment from the debris avalanche into the Toutle–Cowlitz-Columbia river system (Brown, 1987). Debris flows also occurred in Northeastern Victoria, Australia and greatly effected the fluvial system a lot (Rutherford, Bishop, Loffer, 1994). Johnson (1970), with pictures and personal observation, reported on the mud and debris flows at Wrightwood canyon in California, which caused a lot of property damage. A series of debris flows and floods have occurred in the KamiKamihori Zuwa Gully on Mount Yakedake, Japan, the Bebeng River on Mount Merapi, Indonesia and Mizunashi Gawa River on Mount Unzen, Japan (Suwa, 1995).

These are only some examples of the destructiveness of mud, debris and hyperconcentrated flows and there are many more that could be cited in order to emphasize the significance of the study of these kind of flows. If the characteristics of the debris flows that could potentially occur in these areas could be estimated, the design of control structures and forecasting systems would be greatly simplified. However because of the complicated structure of debris flows as well as the stochastic nature of the events that trigger them, there are only a very limited number of tools available for predicting their initiation, movement, and run out conditions.

This paper assesses different methods to predict the mean flow velocity in hyperconcentration, mud and debris flows, which is needed to estimate the impact force for a debris flow for a given set of physical and geometric conditions. These methods can be used to estimate the capacity of natural or man-made channels to convey debris flows. Once the channel capacity is estimated, areas that are prone to debris flow damage can be more readily identified and appropriate mitigation measures can be prescribed. It is therefore suggested that an attempt at reporting mud and debris flow events should focus on a description of the mean flow properties that will assist in developing future predictive methods.

CLASSIFICATION OF HYPERCONCENTRATIONS

The changes in the dynamic and physical characteristics of the fluid because of hyperconcentration of sediments, has certainly provided the researchers enough enthusiasm to study the complex nature of mud and debris flows. It is therefore necessary to understand the basic concepts and classification of highly sediment laden flows before going into the complex details of the subject.

The most common terms being used by different researchers for highly sediment-laden flows are 'hyperconcentrated flows', 'mud flows' and 'debris flows'. Flows with large sediment concentration have been classified according to : 1) triggering mechanism; 2) sediment concentration; and 3) rheological and kinematic behavior (Bradley, 1986).

Debris flow is a mass movement of rock fragments, soil and mud. With decreasing water content debris flow grades into landslides. Debris flow occurs when masses of poorly sorted sediment, agitated and saturated with the water surge down slopes in response to the gravitational attraction. Solid forces (due to the grains) dominate the physics of the avalanches, and fluid forces dominate the physics of floods, solid and fluid forces must act in concert to provide a debris flow. Mud flow is a non-Newtonian fluid mixture of sediment and water which occurs in steep mountain watersheds and desert canyons. Sharp and Nobles (1953) has defined the mud flow simply as a variety of debris flow in which the mud, although not necessarily quantitatively predominant, endows the mass with the specific properties and modes of behavior which distinguish it from flows of debris devoid of mud. Varnes (1978), cited by Pierson and Scott (1985), explains the difference between the debris flow and mudflow on the basis of sediment concentration as follows:

> "At the point where the shear strength of the static mixture becomes sufficient to suspend gravel size particles and the coarse and fine grains are no longer able to settle independently, the flowing mixture becomes a 'debris

flow' or 'mud flow' depending on the gravel content, debris flows have more than 50 percent gravel, mudflows have less".

Hyperconcentrated flow can be defined as a still more or less uniform flow with a high suspended fine material concentration and a viscosity larger than that of water, coarse sediment may be transported as bed load, whereas debris flow can be described as an unsteady, pulsing flow of a mixture of water and both coarse and fine sediment (Rickenmann, 1991).

However the ongoing debate that attributes to the high mobility of classification of hyperconcentrations to be achieved on the basis of sediment concentration only, often encounters lot of arguments questioning the very existence of many other important factors too. At higher concentrations classification by concentration becomes less adequate because the effects of particle size, shape, and distribution gain relative importance as particle collision and interaction increases with increasing concentration. Jeppson and Salvador (1983) have cited an excellent definition of debris flow, by Takahashi (1980) which also emphasizes the importance of sediment size and shape while classifying the highly sediment laden flows. According to that definition "debris flow is a flow of a mixture of all sizes of sediment. Boulders accumulate and tumble at the front of the debris wave and from a hole, behind which follows the fine grained more fluidic debris." Jan and Shen (1993) also state that Fei's (1983) experiments indicate that the mixture behaves as a Newtonian fluid or a non-Newtonian fluid, depends on the content of the fine particles with diameter less than 0.01 mm as well as the sediment concentration.

Hyperconcentrated flows are also classified according to their rheological behavior. According to the rheological behavior as well as sediment concentration, Pierson and Costa (1984) qualitatively classified flows into stream flow, slurry flow, and granular flow. The division between stream flow and slurry flow coincided with the transition between Newtonian and non-Newtonian flow behavior. Various rheological models have been proposed to define the rheology of hperconcentrations. Bingham viscoplastic model (1922), Pseudo plastic model and Dilatant model (Wazer, 1963), and Quadratic model (O'Brien and Julien, 1985) are some examples of such models. Therefore for the sake of simplicity of discussions about the applicability's of the existing rheological models, Jan and Shen (1993) have qualitatively classified debris flows into three categories: 1) granular flow in which fluids effects are negligible; 2) mud flow in which fluid effects are dominant and particle collisions are negligible; and (3) stony debris flow in which particle interactions are important as well as the fluid effects.

MECHANISM OF HYPERCONCENTRATED SEDIMENT FLOWS

The predominant process 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 depends upon the fluid properties, the concentration of sediment and weather the flow matrix includes cohesive sediment. Although the initiation of motion through landslides and creeping soil failures are more properly examined through 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.

For Newtonian fluids, by assuming the pressure distribution to be hydrostatic, the shear stress can be described as a function of dynamic viscosity μ_m and of the rate of deformation as follows:

$$\tau = \mu_m \frac{\partial u}{\partial y} \tag{1.0}$$

In hyperconcentrations and mudflows, however, the shear stress is a complex function of the water and sediment properties comprising the fluid matrix, which limits the direct application of Equation (1.0) for the predictive modeling. The mode of highly sediment laden fluid flow changes according to the governing forces in the flow and the governing forces are related to the interactions between fluid and particles, the inter particle collisions as well as the fluid flow itself. The force balance of this mode of hyperconcentrated flow can be expressed as

$\tau_y + \tau_v + \tau_t + \tau_d = \tau$ (Applied shear stress exerted by weight of sediment - water mixture in the flow direction) where τ_y is the yield stress, τ_v is the viscous stress, τ_t is the turbulent stress, and τ_d is the dispersive stress and τ is the applied shear stress in the direction of flow. Under high rates of shear (coarser material), turbulent stresses (due to the fluid-fluid and fluid particle interactions) and dispersive stresses (due to the inter particle friction and collisions) become dominant. At low rates of deformation (cohesive material), the viscous shear stress and yield stress becomes dominant and the Non-Newtonian flow properties become increasingly complex. A detailed discussion related to the magnitude of each of these resistive shear stresses can be found in H. Hussain's MS thesis "Analysis of different Models to predict mean flow velocity in hyperconcentrations, mudflows and debris flows" submitted to Colorado State University (1999).

STEP WISE PROCEDURE TO CALCULATE THE MEAN FLOW VELOCITY IN HYPERCONCENTRATIONS

Following are the fundamental and theoretical steps involved in the description of the mean flow velocity in hyperconcentrations:

(1) Once the whole theory behind the involvement of various stresses in hyperconcentrations is fully understood, it is possible to define various forms of models which can describe the relationship between shear stress and shear rate ($\tau \sim du/dy$) for non-Newtonian flows i.e. mud and debris flows.

(2) After having knowledge about such ($\tau \sim du/dy$) models for the non-Newtonian flows, and describing the magnitude of various resistive shear stresses ($\tau_y, \tau_v, \tau_d, \tau_t$) and also applied shear stress (τ), it is then possible to integrate those expressions (should be in the form of du/dy

~ function of magnitude of shear stresses) for a certain boundary condition to define the velocity profile in hyperconcentrations.

(3) Once the velocity profile is defined, it is easier to integrate it through the entire flow depth to define the mean flow velocity for hyperconcentrations.

$$V = \frac{1}{h}\int_0^h u dy \tag{2.0}$$

where u is the velocity profile and V is the mean flow velocity in hyperconcentrations and h is the total flow depth. Details of different models that describe the relationship between the shear stress-shear rate ($\tau \sim du/dy$) and velocity profiles for non-Newtonian fluids can be found in several papers published on this topic in international journals.

DIFFERENT MODELS TO PREDICT THE MEAN FLOW VELOCITY IN HYPERCONCENTRATIONS

Below is a brief description of different models that predict the mean flow velocities in hyperconcentrations, mud flows and debris flows:

Jaeggi Model (1983)

Jaeggi (1983) proposed a modified flow resistance equation for a sediment transporting flow over a movable bed at smaller relative depths h/d_{90}, because many conventional formulas tend to over-predict the velocities in the range $5 < h/d_{90} < 20$. His equation is given as:

$$\frac{V}{u_*} = 2.5\left[1 - \exp\left(\frac{\alpha_1 h}{d_{90} S_o^{\ 0.5}}\right)\right]^{1/2} \ln\left(\frac{12.27h}{\beta_1 d_{90}}\right) \tag{3.0}$$

where V is the average fluid velocity; u_* is the shear velocity = $(ghS_o)^{1.2}$; α_1 and β_1 are the coefficients; h is the flow depth; d_{90} is the characteristic grain size, 90% of the material by weight is finer and S_o is the bed slope. Coefficients α_1 and β_1 depend on the grain size distribution and the packing and the shape of the bed material. Rickenmann (1991) has cited Smart and Jaggei (1983) that for the steep channel bed material transport tests, α_1 and β_1 have the values of 0.05 and 15 respectively.

Modified Jaeggi Model

It was observed during the calculation process for the Jaeggi model that the factor $exp\ (\alpha_1\ h/d_{90}\ S_o^{0.5})$ always turns to be greater than one when calculated against all data sets. It was also observed that for the data sets having fine material (finer than sand) the factor $exp\ (\alpha_1\ h/d_{90}\ S_o^{0.5})$ becomes so high that its exponential value cannot be taken. Therefore, the Jaeggi original model (3.0) is then modified by assuming the factor $exp\ (\alpha_1\ h/d_{90}\ S_o^{0.5})$ equal to 0. The modified Jaeggi model can be expressed as:

$$\frac{V}{u_*} = 2.5\ ln\left(\frac{12.27h}{\beta_1 d_{90}}\right) \tag{4.0}$$

The modified Jaeggi model is a turbulent model and describes a logarithmic relationship between the resistance to flow and relative submergence h/d_s as follows:

$$\frac{V}{u_*} = \sqrt{\frac{8}{f}} = 5.75\log\left(\frac{0.818h}{d_{90}}\right) \tag{5.0}$$

Takahashi Model (1978)

The Takahashi model is applicable to the motion of steady uniform debris flow. Takahashi (1978) has proposed an equation for the mean velocity of a quasi-steadily moving debris flow front on the basis of dispersive stresses between the moving grains. He replaced concentration and density terms together with grain–shearing coefficients by one simple parameter A^* and has presented the following expression:

$$\frac{V}{(gd_s)^{0.5}} * \left(\frac{gd^3}{q^2}\right)^{0.3} = A^*(\sin\beta)^{0.2} \tag{6.0}$$

where V is the mean velocity of debris flow front; g is the gravitational acceleration; q is the fluid discharge per unit flume width; d_s is the grain size and β is the bed slope angle. A^* is approximately equal to 1.3 as can be seen from the diagram plotted by Takahashi (1978) for his experimental results in terms of non-dimensional velocity versus bed slope $\tan\alpha$. Rickenmann (1991) transformed Equation (6.0) into the following form:

$$V = \frac{1.3(\sin\beta)^{0.2} q^{0.6} g^{0.2}}{d_s^{0.4}} \tag{7.0}$$

Rickenmann then made the following replacements in Equation (7.0) :

$$\text{Sin}\beta = \tan\beta = S_o$$

$$d_s = d_{90}$$

Equation (7.0) then took the following form:

$$V = \frac{1.3 S_o^{0.2} q^{0.6} g^{0.2}}{d_{90}^{0.4}} \tag{8.0}$$

where V is the average fluid velocity; d_{90} is the characteristic grain size, 90 % of the material by weight is finer; S_o is the bed slope; g is the gravitational acceleration and q is the fluid discharge per unit flume width. However Equation (8.0) can be simplified as follows:

$$V = \frac{1.927 g^{0.5} h^{1.5} S^{0.5}}{d_s} \quad (9.0)$$

where $d_{90} = d_s$

It should be noted that the Takahasi Model is a dispersive model and therefore, the Eq. (9.0) can be also written in terms of Darcy Weisbach friction factor f by defining a relationship between V/u_* and h/d_s as follows:

$$\frac{V}{u_*} = \sqrt{\frac{8}{f}} = 1.927 \frac{h}{d_s} \quad (10.0)$$

Julien Model (1993)

O'Brien and Julien (1985) proposed the following quadratic rheological model for hyperconcentrations which takes care of all four resistive shear stress components:

$$\tau = \tau_y + \mu_m \frac{du}{dy} + \varsigma \left(\frac{du}{dy} \right)^2 \quad (11.0)$$

where τ is the total shear stress; τ_y is the yield shear stress; μ_m is the dynamic viscosity; du/dy is the velocity gradient normal to the flow direction; and ς is the turbulent – dispersive parameter. This physically based quadratic model includes yield, viscous, collision and turbulent stress components. The first term τ_y describes the yield stress due to cohesion between fine sediment particles. The second term explains the viscous stress of the fluid interacting with the cohesive sediment particles. Finally the third term referred to as turbulent-dispersive stress combines the effects of turbulence and effects of dispersive stress induced the collisions between sediment particles.

Based on the above quadratic rheological model, O'Brien, Julien and Fullerton (1993) presented depth–integrated form of the quadratic Equation (11.0) which gives the bed shear stress τ_o as a function of flow depth h and mean flow velocity V as follows:

$$\tau_o = \rho_m g h S_o = \tau_y + \frac{3\mu_m V}{h} + \frac{f_t \rho_m}{8} V^2 + \frac{f_d}{8} \rho_m V^2 \quad (12.0)$$

where f_t and f_d are the Darcy-Weisbach friction factors for turbulent and dispersive stress respectively, τ_y is the yield strength; μ_m is the dynamic viscosity of the mixture; ρ_m is the density of the mixture; S_o is the friction slope, and g is the gravitational acceleration.

The mean flow velocity V can be calculated directly from Equation (12.0) as presented below:

$$V = \frac{-12\mu_m}{(f_t + f_d)\rho_m h} + \sqrt{\left(\frac{12\mu_m}{(f_t + f_d)\rho_m h}\right)^2 - \frac{8\tau_y}{\rho_m(f_t + f_d)} + \frac{8ghS_o}{(f_t + f_d)}} \qquad (13.0)$$

where μ_m is the dynamic viscosity; S_o is the frictional slope; τ_y is the yield strength; ρ_m is the mass density of the mixture; f_t and f_d are the Darcy-Weisbach friction factors for the turbulent and dispersive stress respectively and h is the flow depth.

DATABASE CHARACTERISTICS AND CALCULATION PROCEDURE FOR EACH MODEL

The final database consists of both field and laboratory data related to the debris, mud and hyperconcentrated flows. The details and the material reviewed to set up this database are as follows.

Characteristics of the Field Data

A detailed literary search was conducted to collect the field data related to the hyperconcentrations. Most of the reviewed material did not contain all of the parameters (flow depth, bed slope, grain size, sediment concentration, yield strength and dynamic viscosity) required for this study. The final field database consists of three data sets, Jiangjia Gully (China), Yellow River (China) and Mount St. Helens (USA). The details of all the reviewed material is briefly summarized in the following paragraphs.

Hyperconcentrated flow is a peculiar phenomenon in the Yellow River in China. Extensive amount of data about the Yellow River has been extracted from H. Hussain's MS thesis "Analysis of Different Models to Predict Mean Flow Velocity in Hyperconcentrations, Mudflows and Debris flows" submitted to Colorado State University (1999). The Yellow River data has a maximum sediment concentration of 565 kg/m^3 (volumetric sediment concentration of 21 %).

The database also includes a comprehensive amount of data about the Jiangjia Gully (Academia Sinica, 1989). The Jiangjia Gully data is important not only because it is one of the most frequently occurring debris flow gullies in the world, but also because it provides information about the measured rheological parameters of the flow (yield strength τ_y and dynamic viscosity μ_m), difficult to find in any field data. The Jiangjia Gully data possesses a high sediment concentration, with a maximum value of 2292 kg/m^3, which is important in verifying the effectiveness of the models against such a high sediment concentration.

Many debris flows result from volcanic eruptions. It is difficult to get complete data about these catastrophes because most of the datasets lack the information about the exact velocity of lahar at different cross-sections, the exact flow depth and the rheological properties of flow (yield strength and dynamic viscosity). However, the database does include the data about the famous Mount St. Helens volcanic eruption. Brown (1987) has an extensive amount of data in his dissertation about the Toutle-Cowlitz-Columbia River System from September 30, 1981 to October 1, 1982. This data describes the change in the sediment concentration of these rivers after the Mount St. Helens eruption. Only the data, with a sediment concentration of at least 4%, has been extracted from the Brown's dissertation for this study. In addition Pierson and Scott (1985) have also described in detail the Mount. St. Helens eruption (1982). Some of the relevant data has been taken from their article. Main characteristics of the field data sets have been summarized in the table (1.0).

Table 1.0: Main Characteristics of the Field Data

Database Name	Flow Depth range (m)	C_v Range (%)	Grain Size Range (mm)	Bed Slope (%)	Observed Velocity Range (m/sec)
Jiangjia Gully	0.12 to 3.72	68 to 86	35	5.5 to 6.6	0.57 to 9.56
Yellow River	1.22 to 6.1	3 to 21	0.05	0.0029 to 0.0935	1.097 to 3.73
Mount St. Helens	0.51 to 1.875	4 to 39.6	0.05 to 0.13	0.2 to 0.6	2.12 to 4.27

Characteristics of the Laboratory Data

Much laboratory research all over the world has explored significantly hyperconcentrations, mud and debris flows. In the Early 1950s, Professor Ning Chien began studying the rheological properties of turbid water in China. He not only organized large-scale field surveys of hyperconcentrated flows in rivers, but he and his research group also continued to actively research and organize hyperconcentrated flow studies, through a series of experiments (Wan & Wang, 1994).

Wang, Zang, and Liu 's (1983) experimental study on turbulent characteristics of flow with hyperconcentration of sediment contains excellent data. In this study, concentration of sediment, with a median diameter equal to 0.025 mm, varied from 90 to 666 kg/m^3. The experimental results also contain the rheological parameters.

Past studies on sediment transport in rivers and flumes were mainly concerned with the bed slopes up to a few percent. It was interesting to extend the data base by collecting some data related to sediment transport processes in steep flumes. Extensive amounts of data were found in the Rickenmann (1991) experimental study. The basic purpose of the Rickenmann study was to investigate the hyperconcentrated flow and sediment transport at steep flows. Rickenmann's experimental results include all important parameters required for this thesis. The slope of the flume varied from 5 to 20% whereas maximum density of suspension was 1.36 g/ cm^3.

Mainali and Rajaratnam (1994) also conducted an experimental study of debris flows with a fixed steep slope of flume of 28.6%. Mean volumetric sediment concentration for the flows ranged from approximately 2.5% to 43.5%. Their experimental results are also part of this database.

Detailed information about the different parameters of each laboratory dataset is provided in the Table 2.0.

Table 2.0: Main Characteristics of the Laboratory Data

Database Name	Flow Depth Range (m)	C_v Range (%)	Bed Slope (%)	Grain Size Range (mm)	Observed Velocity Range (m/sec)
Mainali (1994)	0.034 to 0.048	3 to 44	28.6	0.215 to 0.43	2.85 to 3.87
Rickenmann (1990) (A)	0.023 to 0.089	4.8 to 22.1	5 to 20	12	0.75 to 3.38
Rickenmann (1990) (B)	0.045 to 0.0974	4.4 to 22	7 to 20	12	1.11 to 2.75
Wang & Zhang (1983)	0.13 to 0.226	3.4 to 25.1	0.13 to 0.65	0.025	0.51 to 1.223

LIMITATIONS OF THE STUDY

A lot of care has been taken while collecting the data for this study but still to obtain a complete data set is not an easy task. Unfortunately, most of the data sets do not have rheological properties, viscosity and yield stress. Rheological properties of hyperconcentrations are generally formulated as a function of sediment concentration. The recommended empirical formulas are the exponential relationships for yield strengths and viscosity at larger concentrations of fines (Julien, 1994). For this study, yield strength has been estimated by the use of Equations (17.0), (18.0), and (19.0) whereas dynamic viscosity can be estimated by the use of Equations (20.0) and (21.0), if laboratory measurements of these parameters are not available.

Jiangjia Gully data lacks the information about its grain size and different sources report a wide range of grain sizes about the Jiangjia Gully. Therefore various graphs were plotted between V_c and V_{obs} by using different reported grain sizes (5,20,35 and 50 mm) for the Jiangjia Gully. It was observed that the most reasonable fit belongs to a diameter size of 35 mm, therefore this grain size was used for the Jiangjia Gully's calculations. The Yellow River data does not contain any information about the rheological parameters i.e. τ_y (yield strength) and μ_m (dynamic viscosity of the mixture). Both of these parameters are calculated by using Equations (17.0) to (21.0). Similarly Mount St. Helens dataset do not provide any information about τ_y and η and both of these parameters have been calculated by using Equations (17.0) to (21.0). The Mount St. Helens data doesn't provide any information about the slope either. However the relevant slopes have been extracted from the USGS report by Laenen and Hansen (1988). These slopes are also cross-checked by calculating the slopes by the use of Manning's formula. The corresponding value of Manning's roughness coefficient is taken from the Pierson and Scott (1985) article.

At the same time one should not overlook the concerns regarding the accuracy of the measurements. In Rickenmann experimental data set, for some points, velocity was measured by the use of a Salt Tracer technique, not reliable at all, especially at high concentrations because of insufficient mixing of the salt solution in the clay suspensions, as reported by Rickenmann (1991). In Mainali's experimental set up, the surface velocity was determined using a 35 mm camera, a square polyethylene surface float 12.5 mm on each side and approximately 2 mm thick of specific gravity of 0.92. Several images of the float moving downstream were captured in a single frame from where surface velocity was determined. Although the method is extremely simple but a little error can effect the observed value seriously.

CALCULATION PROCEDURE FOR EACH MODEL

In this section, detailed discussion about the different models (which predict the mean flow velocity in hyperconcentrations) has been achieved for a better understanding of the subject. The procedure to calculate the mean flow velocity for each model is also described by providing a stepwise calculation example.

Following are the models.

(1) Julien Model; (2) Modified Jaeggi Model; (3) Takahashi Model

Discussion About the Julien Model

The Julien model requires the following parameters for the calculation of the mean velocity of flow in hyperconcentrations :

(1) The total volumetric sediment concentration (C_{vT}); (2) The channel slope (S_o); (3) The grain diameter (d_s); (4) The flow depth (h); (5) The yield stress (τ_y); (6) The dynamic viscosity (μ_m); (7) The Darcy Weisbach friction factor for turbulence (f_t); (8) The Darcy Weisbach friction factor for dispersive stress (f_d) and (9) The density of mixture (ρ_m).

The channel bed slope (S_o); the particle diameter (d_s) and the flow depth (h) are pure field (river/channel) or laboratory (flume) measurements and do not necessarily require any empirical relationship to calculate them.

The Julien model interestingly involves the effect of turbulence and dispersive stresses both by introducing the factors f_t and f_d respectively. A logarithmic relationship describes the resistance to the turbulent flow as follows:

$$\sqrt{\frac{8}{f_t}} = 5.75 \log \frac{h}{d_s} \qquad (14.0)$$

where f_t is the Darcy- Weisbach friction factor for the turbulence; h is the mean flow depth and d_s is the grain diameter. However, at high concentrations of the non-cohesive granular sediment, resistance to flow increases beyond turbulent flows and the analysis of dispersive stress yields a linear relationship between V/u_* and h/d_s, or

$$\sqrt{\frac{8}{f_d}} = \frac{h}{5d_s} \qquad (15.0)$$

where f_d is the Darcy- Weisbach friction factor for the dispersive stress.

The mass density of the mixture ρ_m can be calculated as follows :

$$\rho_m = \rho(1 - C_v) + \rho_s C_v \qquad (16.0)$$

where C_v is the total volumetric sediment concentration; ρ is the mass density of the fluid (approximately equal to 1000 Kg/m^3) and ρ_s is the density of the solid particles.

In order to have accurate comparisons between the measured and calculated velocities, it is really worth seeking out those data sets which include laboratory measurements of rheological parameters i.e. yield strength (τ_y) and dynamic viscosity (μ_m). However, if not possible, both of these parameters can be estimated by using the following empirical relationships proposed by Julien (1995):

Yield Strength (τ_y) of a mixture (C_v > 0.05)

τ_y(in Pa) = 0.1 $e^{3(C_v - 0.05)}$ for sands (17.0)

τ_y(in Pa) = 0.1 $e^{13(C_v - 0.05)}$ for 95% silts and 5% clay. (18.0)

τ_y (in Pa) = 0.1 $e^{23(C_v - 0.05)}$ for 70 % silts and 30 % clays. (19.0)

Dynamic Viscosity (μ_m)

$\mu_m = \mu\,(1 + 2.5C_v + e^{10(C_v - 0.05)})$ for sands. (20.0)

$\mu_m = \mu\,(1 + 2.5C_v + e^{23(C_v - 0.05)})$ for silts and clays. (21.0)

Calculation Procedure for the Julien Model

The procedure to calculate the mean flow velocity in hyperconcentrations by the using the Julien model can be summarized as follows:

Step 1. Estimate the yield strength (τ_y) from either laboratory measurements or from Equations (17.0), (18.0), and (19.0).

Step 2. Estimate the dynamic viscosity (μ_m) from either laboratory measurements or from Equations (20.0) and (21.0).

Step 3. Calculate (ρ_m) by use of Equation (16.0).

Step 4. Calculate the ratio h/d_s.

Step 5. Calculate f_t by use of Equation (14.0).

Step 6. Calculate f_d by use of Equation (15.0).

Step 7. Calculate the mean flow velocity *in* hyperconcentrations by use of Equation (13.0)

Step 8. Calculate the estimation error related to the computed velocities as follows:

$$[(V_c - V_{obs}) \ / \ V_{obs}] * 100 \quad (22.0)$$

where V_c relates to the computed velocity and V_{obs} is the observed or measured velocity.

Calculation Example for the Julien Model

Available Data:

(1) Observed Depth (h) = 2.00 m; (2) Frictional Slope (S_o) = 0.063; (3) Yield Strength (τ_y) = 43.35 Pascal; (4) Dynamic Viscosity (μ_m) = 1.55 Pascal-second; (5) Grain Size (d_s) = 0.035m; (6) Concentration by Volume (C_v) =0.50; (7) Observed Flow Velocity (V_{obs}) = 7.89 m/sec; (8) Mean Flow Velocity (V) = ?

Step 1. Estimate the yield strength τ_y either from the laboratory measurements or by using Equations (17.0), (18.0) and (19.0). (In this calculation example (τ_y) has been obtained from laboratory measurements).

Step 2. Estimate the dynamic viscosity (μ_m) either from the laboratory measurements or by using Equations (20.0) and (21.0). In this calculation example (μ_m) has been obtained form laboratory measurements).

Step 3. Using Equation (16.0), calculate the mixture density (ρ_m) as follows:

$$\rho_m = 1000 * (1 - 0.50) + (2650 * 0.50) = 1825 \text{ kg/m}^3$$

Step 4. Calculate the ratio h/d_s as follows:

$$h \ / \ d_s = 57.14$$

Step 5. Calculate f_t by use of Equation (14.0) as follows:

$$f_t = 8 \ / \ [5.75 * \log(h \ / \ d_s)]^2 = 0.078$$

Step 6. Calculate f_d by use of Equation (15.0) as follows:

$$f_d = 8 \ / (h \ / \ 5d_s)^2 = 0.06$$

Step 7. Calculate the mean flow velocity V in hyperconcentrations by use of Eq.(13.0):

$$V = \frac{-12*1.55}{(0.078+0.06)*1825*2} + \sqrt{\left(\frac{12*1.55}{(0.078+0.06)*1825*2}\right)^2 - \frac{8*43.35}{1825*(0.078+0.06)} + \frac{8*9.81*2*0.063}{(0.078+0.06)}}$$

V = 8.42 m/sec.

Step 8. Calculate the estimation error related to the computed velocities as follows:

$[(V_c - V_{obs}) / V_{obs}] * 100 = [(8.42 – 7.89) / 7.89] *100$

= 6.7 %

where V_c relates to the computed velocity and V_{obs} is the observed or measured velocity.

Discussion About the Modified Jaeggi Model

The theoretical background of the modified Jaeggi model has already been described earlier in this paper. A brief discussion about the different parameters of the modified Jaeggi model for the calculation of the mean flow velocity in hyperconcentrations has been achieved in the coming paragraphs. The following are the required parameters:

(1) the channel slope (S_o); (2) the particle diameter size of (d_s); (3) the estimated flow depth (h); (4) acceleration due to the gravity (g); (5) empirical coefficients, (α_1 and β_1).

The channel slope (S_o), the particle diameter (d_s,) and the estimated flow depth (h) are pure field or laboratory measurements and do not necessarily require any empirical relationship for their calculation.

Calculation Procedure for the Modified Jaeggi Model

The procedure to calculate the mean flow velocity in hyper concentrations by the use of the modified Jaeggi equation can be summarized as follows:

(1) Calculate the shear velocity $u_* = (ghS_o)^{0.5}$

(2) Choosing β_1 = 15, calculate the mean flow velocity for hyperconcentrations by the modified Jaeggi model by using Equation (4.0).

Calculation Example for the Modified Jaeggi Model

Available Data:

(1) Observed Depth (h) = 2.00 m; (2) Bed Slope (S_0) = 0.063; (3) Grain Size (d_s) = 0.035 m; (4) α_1 = 0.05; (5) β_1 = 15; (6) Observed Velocity; V_{obs} = 7.89 m/sec; (7) Mean Flow Velocity (V) (m/sec) = ?

Mean flow velocity can be calculated by use of the modified Jaeggi equation (4.0) as follows: (by replacing d_{90} by d_s)

$$V = 2.5\,(ghS_o)^{0.5} \ln\left(\frac{12.27h}{\beta_1 d_s}\right)$$

$$V = 2.5*(9.81*2*0.063)^{0.5}\ \text{In}\ [(12.27*2)/(15*0.035)]$$

$$V = 10.68 \text{ m/sec}$$

The estimation error related to the computed velocity can be calculated as follows:

[$(V_c - V_{obs}) / V_{obs}$] * 100 = [(10.68 - 7.89) / 7.89] * 100 = 35.36%

Discussion About the Takahashi Model

The theoretical background of the Takahashi model has already been described earlier in this paper. A brief description of details that are required to estimate the mean flow velocity in hyperconcentrations using Takahashi Model are provided below.

Calculation Example for the Takahashi Model

In order to calculate the mean flow velocity in hyperconcentrations by use of the Takahashi model (Equation 9.0), following data is required: (1) Bed slope (S_o); (2) Grain diameter (d_s); (3) Flow depth (h); (4)Acceleration due to gravity (g)

Available Data

(1) Observed depth (h) = 2.00 m, (2) Frictional Slope (S_f) = 0.063; (3) Grain Size (d_s) = 0.035 m; (4) Observed Velocity = 7.89 m/sec; (5) Acceleration due the gravity (g) = 9.81 m/sec^2

The mean flow velocity in hyperconcentrations can be calculated by using the Takahashi model (9.0) as follows:

$$V = \frac{1.927 g^{0.5} h^{1.5} S^{0.5}}{d_s}$$

$$V = \frac{1.927*9.81^{0.5}*2^{1.5}*0.063^{0.5}}{0.035}$$

$$V = 57.71 \text{ m/sec}$$

The estimation error related to the computed velocity can be calculated as follows:

$[(V_c - V_{obs}) / V_{obs}]$* 100 = [(57.71 - 7.89) / 7.89] * 100

= 631.44 %

where V_c relates to the computed velocity and V_{obs} is the observed or measured velocity.

ANALYSIS OF RESULTS

All the models are tested against this field and laboratory database. Detailed calculations related to the estimation of mean velocity for hyperconcentrations, mudflows and debris flows using the aforementioned models can be found in H. Hussain's MS thesis "*Analysis of different Models to predict mean flow velocity in hyperconcentrations, mudflows and debris flows*" submitted to Colorado State University (1999).

Graphs are plotted to check the predictive capabilities of each model. These include: $V_c \sim V_{obs}$

where V_c = Calculated Velocity

V_{obs} = Observed Velocity

Field and laboratory data sets are compared with each other by plotting them on a same graph against each model (Figure 4.5, 4.10, 4.15, 4.20, 4.25). The effectiveness of each model is described by evaluating the computed results within ± 50% of the measured mean flow velocities. Estimation error associated with the calculated velocities is defined as follows:

$$\frac{V_c - V_{obs}}{V_{obs}} * 100$$

ANALYSIS OF THE JULIEN MODEL

The Julien model has shown a reasonable performance against the field data with 67% of the predicted velocities lie within ± 50% of the measured flow velocities. The Yellow River data shows reasonably good results with 70% of the computed velocities fall within ± 50% of the measured flow velocities. For the Jiangjia Ravine, 63% of the computed mean velocities fall within ± 50% of the measured values. The Mount St. Helens data is the only field dataset for which the Julien model has not shown reasonable results. Only for 29% of this data, the computed velocities stay within ±50% of the measured flow velocities.

The Julien model has show poor performance against the laboratory data with only 25% of the predicted velocities lie within ± 50% of the measured flow velocities. The reason for Julien Model to show a poor performance against the laboratory data is due to its poor performance against entire of the Rickenmann's experimental data set (A&B). For rest of the laboratory data, Julien model has performed reasonable well. For 100% of the Mainali laboratory data, the estimation error between the measured and computed velocities is within ± 50%. It should be noted that for the Mainali experimental data set, the yield stresses are very small because the yield strength of the mixture primarily depends upon the sediment concentration by volume of the fluid matrix of fine sediments (particles finer than 0.0625 mm), whereas, in the Mainali experiment, sand particles of 0.43, 0.335 and 0.225 mm are used. The viscous stresses are also negligible because the mixture viscosity is almost equal to the viscosity of the clear water due to the use of sand particles. Predominance of turbulent stresses in the Mainali data is justified due to the fluid - fluid and fluid-particle interactions. The Julien model also shows good agreement between the measured and calculated velocities for the Wang (1983) experimental data. For Wang (1983) experimental dataset, about 75% of the computed velocities stay within ± 50% of the measured values. Figure 1 presents a comparison between the field and laboratory datasets against the Julien model.

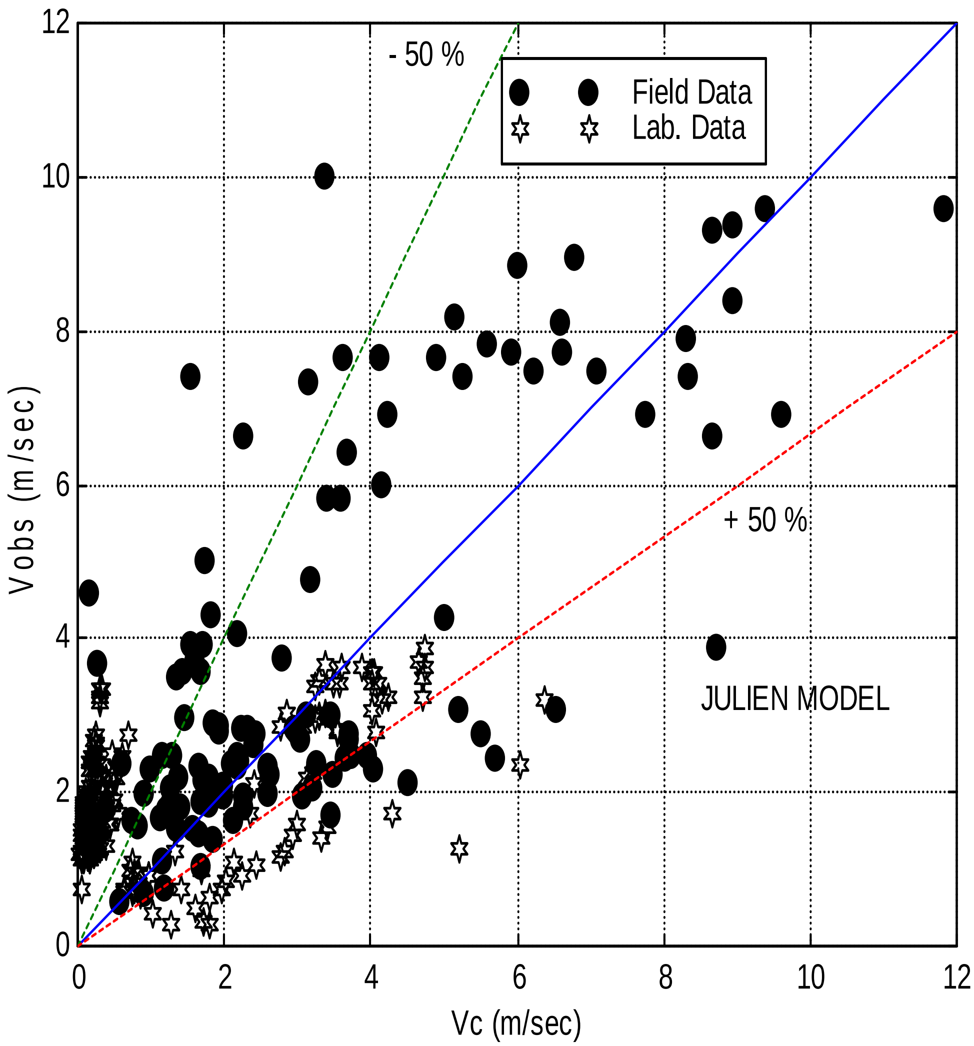

Figure 1: Comparison between the Field and Laboratory Data Against the Julien Model.

Analysis of the Modified Jaeggi Model

The modified Jaeggi model has shown reasonable results for the field data with 76% of the computed velocities stay within ± 50% of the measured flow velocities; this is more accurate than any other model tested. For the modified Jaeggi model, the calculated velocity is directly proportional to the flow depth and inversely proportional to the grain size and an empirical coefficient, B_1. The model agrees well with the Jiangjia gully and the Yellow River datasets. For 85% of the Jiangjia Gully data, the calculated velocities stay within ± 50% of the measured flow velocities. For the Yellow River data, 76% of the computed velocities lie within ± 50% of the measured values. However, the model has shown relatively poor performance for the Mount St. Helens dataset. For the Mount St. Helens dataset, only 15% of the computed values fall within ± 50% of the measured flow velocities. The likely reason for the model to show such a high overestimation could be the very fine grain size and steep slopes in the Monunt St Helens Data Set. It is interesting to note that all of the models have overestimated the Mount St. Helens data, which indicates a possible error in the measurement of the field velocity for the Mount St. Helens data.

The modified Jaeggi model has also shown promising results for the laboratory data with 93% of the laboratory data lies within ± 50% of the measured flow velocity, excluding Rickenmann data set A. If Rickenmann dataset A is also included in the analysis, 58% of the computed velocities stay within ± 50% of the measured flow velocities. It should be noted that in the modified Jaeggi model the dependent variable 'V' is directly proportional to the flow depth (h), and the bed slope (S), and inversely proportional to the grain size (d_s). Both of the Rickenmann data sets (A and B) posses almost similar parameters. The bed slope varies between 5 and 20% for (A) and between 7 and 20% for (B). Grain size is identical in both cases (10 mm). The only difference between these two datasets is the flow depths. For almost 90% of the Rickenmann data set (A), flow depth ranges between 23.6 and 60 mm whereas for 90% of the Rickenmann dataset (B), flow depth varies between 50 and 98 mm. Due to these lower flow depths, the modified Jaeggi model underestimated the whole Rickenmann dataset (A) so heavily as compared to the Rickenmann dataset (B). This indicates the sensitivity of the model against the flow depth as compared to the bed slope and grain size. The model has shown excellent agreement with the Mainali database with all of the computed results lying within ± 50% of the measured flow velocities. The model shows moderate performance for Wang's dataset with 58% of the computed velocities lying within ± 50% of measured flow velocities. Figure 2 presents a comparison between the field and laboratory datasets against the Modified Jaeggi Model.

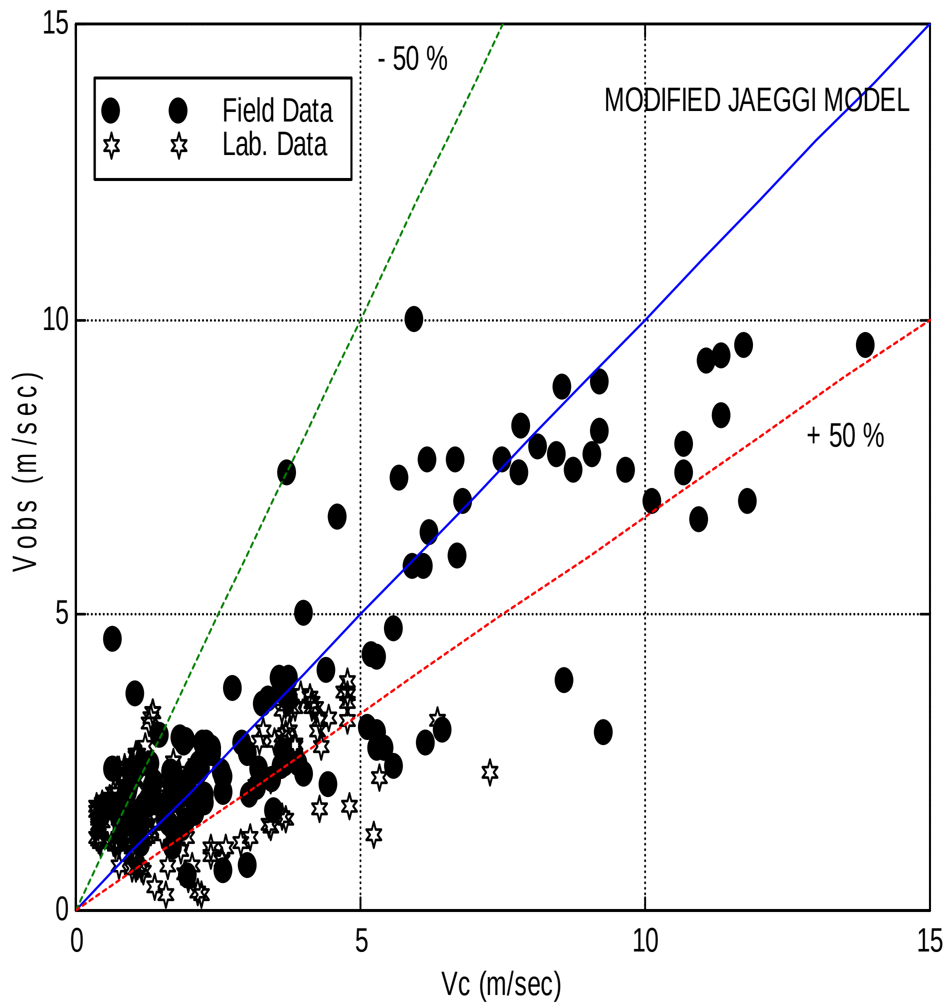

Figure 2: Comparison between the Field and Laboratory Data Against the Modified Jaeggi Model

Analysis of the Takahashi Model

Before going into the detailed analysis of the Takahashi model results, it should be pointed out that the Takahashi model was originally derived on the concept of dispersive stresses resulting due to the inter momentum transfer between the neighboring layers due to the grain collisions. Accordingly, the Takahashi model has shown poor agreement for the most of the field and laboratory data, because almost the whole examined database is basically either turbulent or viscous with Rickenmann database as an exception. In the Takahashi model, velocity, V_c , is inversely proportional to the grain size, d_s. Due to the fine material, the model predicts high velocities.

For nearly 100% of the field data, there is almost no computed velocity lying within ± 50% of the measured flow velocity (except one point in the Jiangjia gully data). It was observed that the Takahashi model is very sensitive to the ratio between the flow depth and the grain size or in other words, against the relative submergence (h/d_s). The higher the h/d_s ratio is, the higher the estimation error would be. For the Jiangjia gully data, h/d_s ratio varies between 3.43 and 78.57 (grain size of 35 mm) and the estimation error between the measured and calculated velocities varies between –22.761 and 2216 %, much better than what was observed for the rest of the field data. For example, for the Yellow River data, h/d_s ratio is very high varying between 21600 and 122000 (due to the very fine grain size of 0.05 mm) and accordingly, the estimation error is also very high ranging between 69630 and 1616839%. Similarly, for the Mount St. Helens data, the h/d_s ratio varies between 7615 and 35320 and the estimation error between the measured and calculated velocities varies within 138333 and 620857%. This shows that the Takahashi model does not simulate viscous or even turbulent datasets that well (data sets with extremely high values of h/d_s). It indicates its weakness for the fine grain size that is very common in hyperconcentrations occurring in the field.

The Takahashi model has predicted unrealistic results for the laboratory data similar to the field data. Excluding the Rickenmann experimental dataset A, the rest of the laboratory data has been severely overestimated (greater than +50%) by the Takahashi model. For the experimental dataset (A), almost 90% of the computed velocities stay within ± 50% of the measured flow velocities. The reason for Takahashi model to highly overestimate the laboratory data is again the sensitivity of the model to the ratio of flow depth to the grain size or against the relative submergence, h/d_s. Figure 3 presents a comparison between the field and laboratory datasets against the Takahashi Model.

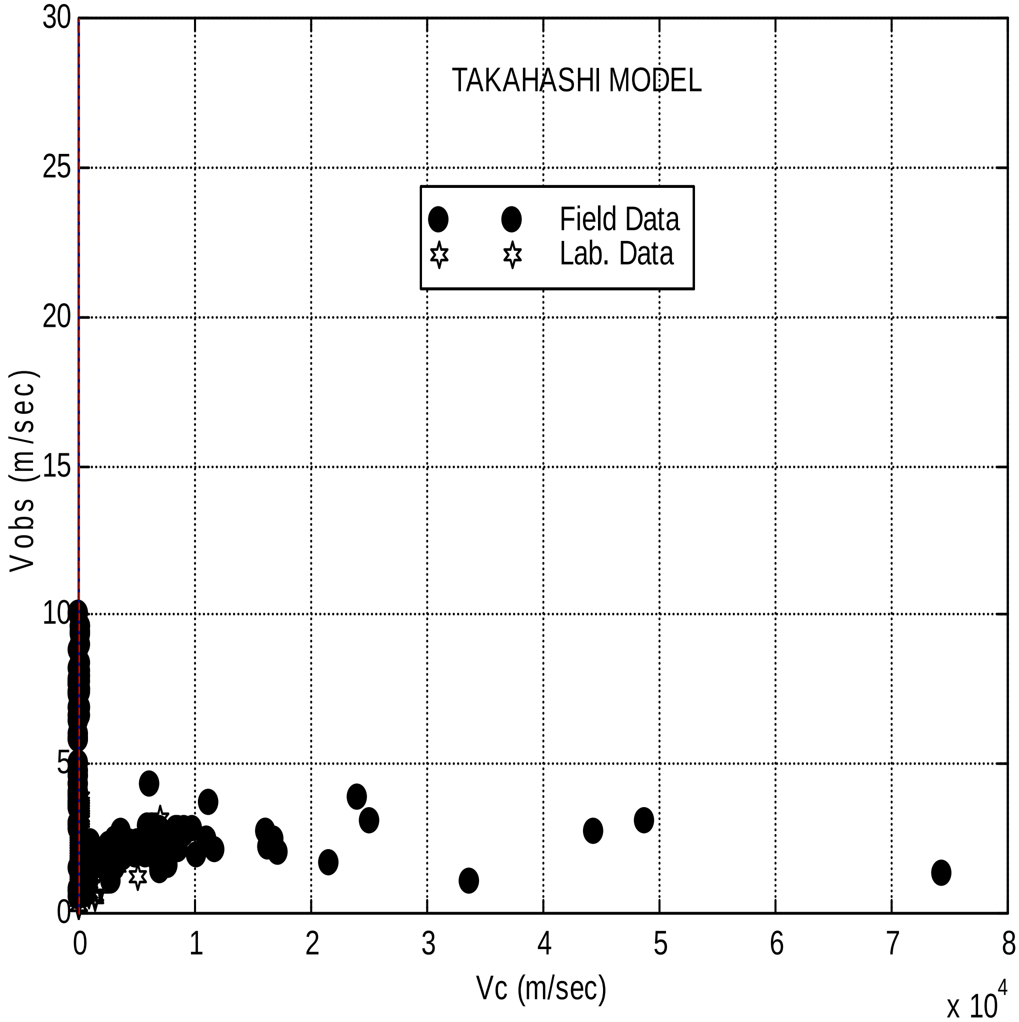

Figure 3: Comparison between the Field and Laboratory Data Against the Takahashi Model.

SUMMARY OF RESULTS

Table (3.0) provides the summary of the percentage of computed velocities by different methods falling within ± 50% of the measured mean flow velocities.

Table 3.0: Percentage of Computed Mean Velocities Falling Within ± 50% of the Measured Mean Flow Velocities

Models	Field Data	Laboratory Data
Modified Jaeggi Model	76%	58% (95% without Rickenmann A data set)
Julien Model	67%	25%
Takahashi Model	0%	37%

Table (4.0) compares different models by summarizing the percentage of overestimated and underestimated computed velocities by each method.

Table 4.0: Percentage of Overestimated and Underestimated Computed Velocities

Models	Field Data (% of Overestimated Computed Velocities)	Field Data (% of underestimated computed velocities)	Lab. Data (% of overestimated computed velocities)	Lab. Data (% of underestimated computed velocities)
Modified Jaeggi Model	50	50	30	70
Julien Model	35	65	20	80
Takahashi Model	100	0	82	18

CONCLUSIONS

From the analyses of the field and laboratory datasets, the following conclusions can be formulated:

1. The Takahashi model (dispersive) overestimates both field and laboratory data quite heavily (See Tables 3.0 and 4.0). This shows that the dispersive stresses do not play an important role among hyperconcentrations, mud and debris flows as claimed by Takahashi (1978). The sensitivity of the Takahashi model is observed against the relative submergence h/d_s. The detailed analysis of the Takahashi model also shows that the greater the h/d_s ratio, the greater the estimation error. This indicates the suitability of the model for those kinds of flows that contain larger grain size and lower flow depths (i.e. Rickenmann data set A).

2. The Julien model has shown a reasonable performance against the field data with 67% of the predicted velocities lie within ± 50% of the measured flow velocities but performs poorly against the laboratory data with only 25% of the predicted velocities lie within ± 50% of the measured flow velocities. It should also be noted that only the Julien model includes the effect of all four stresses i.e. yield, dynamic, viscous and turbulent for the description of the mean flow velocity in hyperconcentrations. All other models are either turbulent, dispersive or Bingham. The Julien model, however, shows better results for turbulent data sets (Mainali and Yellow River) and underestimates dispersive data sets (Rickenmann A and B). This indicates that the present formulation used by Julien (1993) to describe the resistance to flow for dispersive stress (Equation 15.0) needs to be revised. Perhaps Takahashi's proposed formulation to describe the resistance to flow for dispersive stress (Equation 10.0) could be used in the Julien model. For the Julein model it is also observed that the model overestimates all those data sets (Mount St. Helens) for which the rheological parameters (τ_y and μ_m) are estimated by using the empirical equations (17.0 to 21.0). This indicates that the above-mentioned empirical equations overestimate the rheological parameters, τ_y and μ_m, which results in the over-prediction of the velocity by the Julien model.

3. The modified Jaeggi model (turbulent) shows best results among the models discussed. For the modified Jaeggi model, the computed mean velocities for the 76% of the field data and 58% of the laboratory data fall within ± 50% of the measured flow velocities. The modified Jaeggi model, however, does not simulate the laboratory data that well, especially it underestimates the Rickenmann data set A (Table 3.0). Perhaps it is due to the reason that Rickenmann data set A is dispersive due to the lower flow depths and the larger grain size (12mm). For the modified Jaeggi model, sensitivity of the model is also observed against the flow depth especially for the laboratory data set.

4. The above conclusions indicate that the mean flow velocity for hyperconcentrations can be well predicted by the turbulent models (such as the Modified Jaeggi Model). This shows the predominance of the turbulent stresses in hyperconcentrations, mud and debris flows as compared to the dispresive, yield and viscous stresses likewise the ordinary sediment laden flows.

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