Physical and Numerical Study of Debris Flows from Dolomite Slopes Exposed in the 2005 Kashmir Earthquake, Pakistan

Z. A. Kazmi & K. Konagai
University of Tokyo, Japan

T. Ikeda
Tobishima Corp., Japan

SUMMARY:
A devastating earthquake occurred in Kashmir, Pakistan on October 8th, 2005. This earthquake resulted from reactivation of a known active fault later defined as the Balakot–Bagh fault, which caused widespread slope failures throughout its stretch, particularly around Muzaffarabad, the provincial capital of Azad Jammu and Kashmir. These slope failures resulted in a huge amount of debris material which flows in deeply incised creeks during monsoon and hits the inhabitants along the valley in Muzaffarabad. Two GPS measurements are carried out along with channel morphometric parameters and observed changes to investigate the effect of debris flows along these creeks during monsoon. Other than the physical measurements, actual debris flow is simulated using the Depth Average Material Point Method (DAMPM) after carrying out parametric study and calibrating the model for subject topographical and geological settings.

Keywords: Kashmir Earthquake, debris flow, GPS, Depth Average Material Point Method, calibration

1. INTRODUCTION

Rock weathering, rock slides and fault ruptures as a result of huge earthquakes in mountainous areas often develop substantial sources of debris material which travel long distances in drainage channels, usually having very steep gradients, and cause serious destruction of large areas. Urban developments generally expand on valley fills to the foot of the mountain ranges, exposing increased number of lives and property to this danger. A devastating earthquake occurred in Kashmir, Pakistan on October 8th, 2005. The source of the earthquake was the northwest-striking Balakot–Bagh (B–B) fault (Balakot-Garhi fault by Kumahara and Nakata, 2006) with surface rupture and vertical dislocation causing thousands of landslides and debris sources throughout its stretch. Every year during heavy monsoon rains, this loose material flows down to the flat valleys causing fatalities, destroying roads and disrupting communication.

This paper focuses on quantitative measurements using differential GPS, morphometric parameters and observed changes to investigate the threatening effect of the debris flows. These measured debris flows of two catchments in the lesser Himalayas, north of Pakistan, are analysed using the Depth Averaged Material Point Method (DAMPM) (Abe et al., 2007). The effect of different input parameters on debris flow runout features is studied in detail and the model is calibrated comparing its outcomes with measured features, mainly in terms of velocity and flow depth to illustrate its validation for debris flow risk assessment in areas of similar geomorphological conditions.

2. PHYSIOGRAPHY AND GEOLOGICAL SETTINGS

The study area lies in the lesser Himalayas, in Pakistan administrated Jammu-Kashmir. The climate of the area is monsoonal with an average annual precipitation of about 1510 mm, with a major portion falling as rain during the monsoon season (July-September).

The area devastated by the Kashmir earthquake is traversed by the Main Boundary Thrust (MBT) defining Hazara-Kashmir Syntaxis (HKS) (Fig. 1). The causative Balakot-Bagh (B-B) fault, mapped by the Geological Survey of Pakistan prior to the earthquake, cuts HKS offsetting the MBT at the location where the MBT bends sharply from northwest to south (Fig. 1). The fault has reverse separation with the northeast side moved up, which has been verified by high crustal deformation from satellite data and fault modeling (Sato et al., 2007). Slope failures are present all along the active fault, but most serious around Muzaffarabad city for its extent and long lasting problems. Around Muzaffarabad city, failures occurred in Muzaffarabad Formation which forms steep valley slopes and comprises thinly bedded and highly fractured dolomite constituting the lower beds in the hanging wall of Balakot-Bagh fault. This fractured loose material is a big source of debris. During the heavy rains of the monsoon, this loose material combined with water moves as debris flows in the deeply incised creeks directing and inundating the relatively flat, well inhabited valley of Muzaffarabad (Fig. 2). For the subject study, the authors selected the two most damaging creeks namely "Gulshan" and "Tariqabad" (Fig. 2).

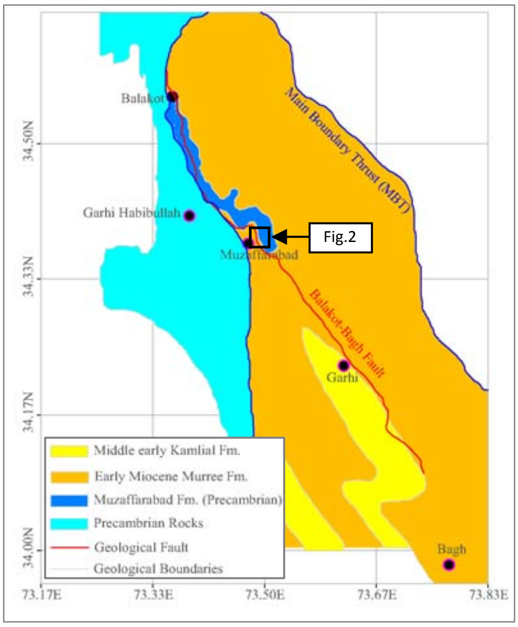

Figure 1. Simplified geological map of the devastated area with overlaid fault map

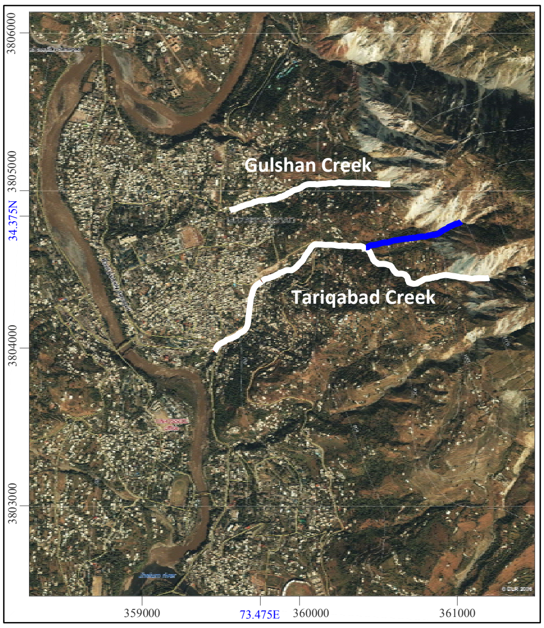

Figure 2. Exposed debris source behind Muzaffarabad city and incised creeks feeding Neelum River (Modified from IKONOS © SPACEIMAGING 2005)

3. PHYSICAL MEASUREMENTS

3.1. GPS Measurements

Two GPS measurements were taken enclosing the monsoon season, June 2008 and November 2008, along Gulshan and Tariqabad creeks. The differential GPS system is used with one receiver installed at the fixed reference point (34.3662^{o}N 73.4759^{o}E), while the others worked as a kinematic station taking measurements at a number of points marked along the selected creeks. Two different measurements are taken: one along the lowest incised ditch to investigate the creek bed erosion and deposition, and the other with additional three points at each remarkable bend of the creek to define the flow cross-section and to estimate flow velocities from outer and inner flow boundaries that can be defined from available traces of debris material and/or mud marks along the banks.

The points marked along both the creeks during two surveys do not match completely due to change in location of the incised ditch. Therefore, all the measured points for each creek are projected upon an upright plane, a kinked line when viewed from directly above with each piece of line best fitting each corresponding group of marked points in a least square sense, in order to discuss creek-bed erosion and deposition. Fig. 3 shows the plane profiles of both the channels, showing all the marked points along with the common projection planes. Since the points marked in June and November mismatch longitudinally, curves are fitted to the elevation plots of marked data points using spline cubic function for quantitative evaluation. For increased accuracy and smoothness of fitted curves, measured data points are divided into a number of groups, each is a set of a few controlling GPS marked points having similar trend in elevation plot. This curve-fitting gives an assumed profile between two marked points and may involve some error, but is a way to quantitatively evaluate erosion and deposition. By taking points measured in June with fitted curves as a reference, due to the better GPS positional accuracy in June (Geometric Dilution of Precision (GDOP) <3.0), erosion and deposition analysis is carried out along the entire lengths of the creeks. The detailed erosion deposition analysis and other observations are explained in the following sub-sections separately for each creek.

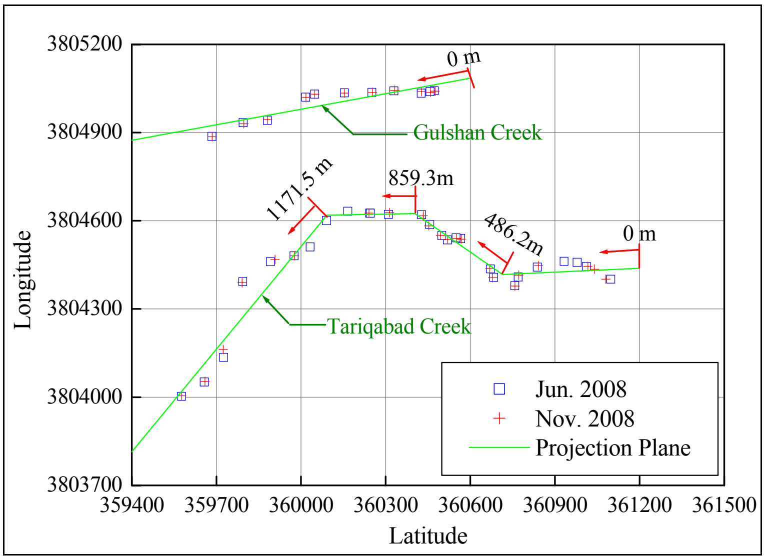

Figure 3. Marked data points along Gulshan and Tariqabad creeks along with common projection planes (with UTM coordinates

3.1.1. Gulshan Creek

Gulshan Creek has a reasonably straight configuration. The total surveyed length of this creek was about 900m with an average slope of 12.9^{o}. Fig. 4a shows the elevation difference from June 2008 to November 2008 with respect to each distance from the accessible source along the projected plane, together with the creek-bed gradient. Since the elevation difference is determined with reference to June data, positive values indicate deposition while negative values indicate erosion. The initial length above the point of 230m distance is the initiation zone with the bed gradients larger than 20^{o}, verified by repeated field surveys. The very high depositional depth of about 2 to 3m shown in this zone is due to the accumulation of loose fractured material from the steep catchment of the creek which is then mobilized by rain water. Downstream of the point of 540m distance, most values are positive along the channel with the gradients smaller than 10^{o}, defining the deposition zone, which strongly agrees with our field observations. Data shows a depositional depth of up to 0.9m, with less depth at around 850m distance where material has been removed by local people for their use. Between these two zones, both erosion and deposition have occurred, defining the flow and transportation zone with the bed gradient between 10^{o}-20^{o}. Erosions and depositions appear alternately in this reach reflecting channel configuration and bed slopes. Inhabitants live mostly in the depositional zone, suffering from repeated events during monsoon (Fig. 4b and 4c).

3.1.2. Tariqabad Creek

In contrast to Gulshan creek, Tariqabad creek has an irregular configuration. The total surveyed length was about 1900m with an average slope of 11.8^{o}. The elevation difference from June to November, with respect to June data, is shown in Fig. 5 together with the channel bed slope. The initial length above the point of 275m distance from the accessible source is responsible for the initiation of the debris flow with a bed gradient larger than 16°. This reach has very steep channel banks with highly fractured loose debris material. This material flows down the steep slopes and is accumulated in the creek from where it is transported by the already mobilized debris mass from slightly upstream sources. GPS data indicates erosion in this reach, which is due to the transportation of accumulated material, and it takes time for new debris to accumulate again. Downstream of the point of 1340m distance, data shows deposition along the channel with a gradient smaller than 10°, defining the deposition zone. The depositional reach is relatively long with more depositional depth as compared to Gulshan creek, which may be attributed to long length, irregular configuration and tributaries feeding at the lower reach of the channel. Some points in this depositional zone indicate erosion which has resulted from man-made changes and excavation of deposited material, observed during survey. Between both of the above mentioned zones is the flow and transportation zone where both erosion and deposition are indicated depending on the channel configuration and bed gradient. This flow and transportation zone has the bed gradient between 10°-16° with some local high values.

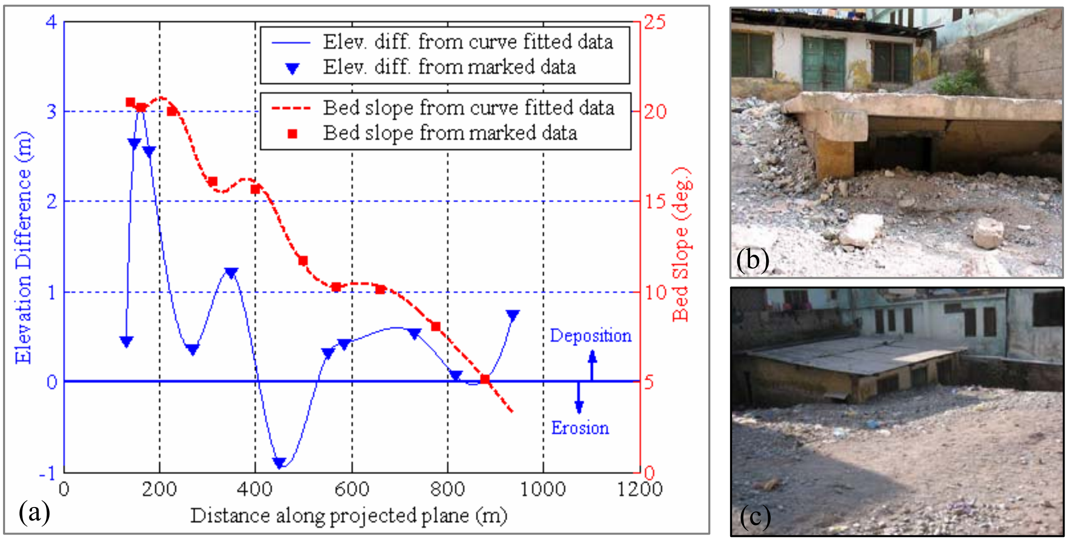

Figure 4. a) Elevation difference from June 2008 to November 2008 along Gulshan creek together with bed slope. b) and c) are the photographs taken in August 2007 and November 2009, respectively, showing the houses half to full buried in debris mass along the depositional zone.

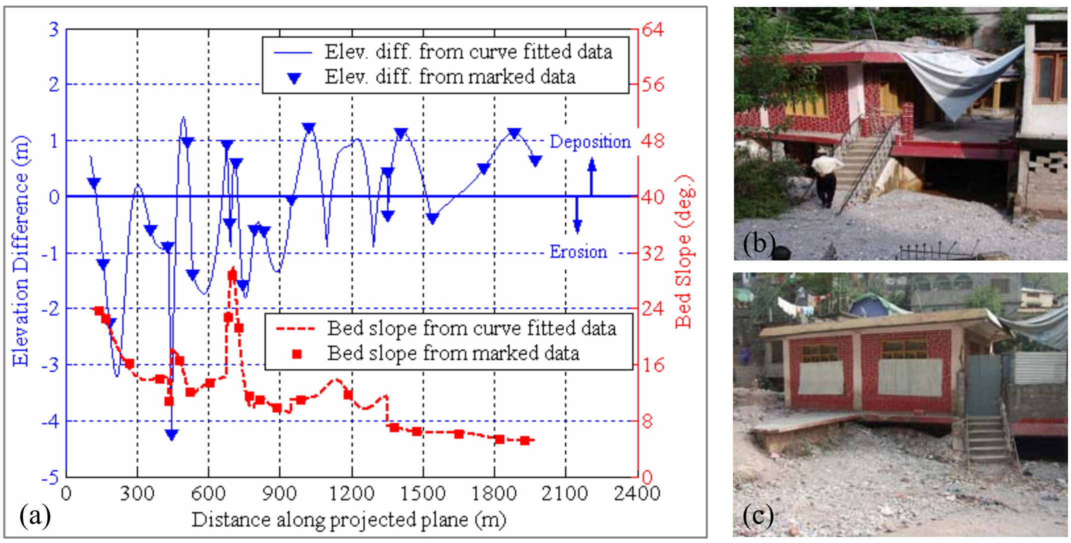

Figure 5. a) Elevation difference from June 2008 to November 2008 along Tariqabad creek together with bed slope. b) and c) are the photographs taken in November 2006 and November 2009, respectively, showing the houses half to full buried in debris mass along the depositional zone.

3.2. Channel Morphometric Parameters

During the second survey, 11 cross sections of both the creeks were measured at bends (Fig. 6 and Table 1). At each section, the velocity of debris flow is estimated from superelevation of lateral deposits or mud lines according to Johnson et al., 1984 as:

$$v = \sqrt{\frac{R_c g}{k}\frac{\Delta h}{b}} \quad = \quad \sqrt{\frac{R_c g}{k}\tan(\beta)} \tag{3.1}$$

where, R_c is the radius of curvature of the center line of channel bend, g is the acceleration due to gravity, k is the correction factor for viscosity and vertical sorting, Δh is the superelevation of flow, b is the flow width, and therefore β is the angle of tilting debris surface. A correction factor of unity is used for relatively straight reaches while 2.5 for very sharp bends where shock waves can develop.

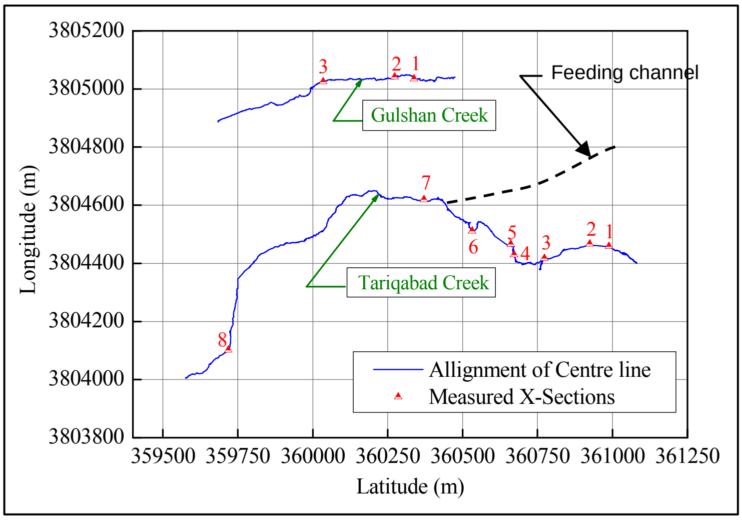

Figure 6. Plane profiles of Gulshan and Tariqabad creeks along with locations of cross-sectional measurements to estimate the flow velocity and discharge

Table 1. Morphometric measurements along Gulshan and Tariqabad Creeks

Creek	Section #	Depth	Width	β (°)	R_c (m)	v (m/sec.)	Q (m^3/sec.)
Tariqabad	1	1.20	3.30	11	52.38	6.32	25.03
	2	1.10	3.10	7	N/A	N/A	N.A
	3	0.60	8.50	4	53.57	3.83	19.55
	4	0.50	5.60	6	40.48	4.09	11.44
	5	0.60	4.30	8	16.67	3.03	8.47
	6	0.60	5.10	8	15.48	2.93	8.97
	7	1.20	10.00	5	65.48	4.74	56.90
	8	N/A	12.00	3	45.24	3.05	N/A
Gulshan	1	1.30	9.10	7	37.52	6.72	79.53
	2	1.15	9.60	8	34.72	6.92	76.39
	3	1.20	5.80	4	41.67	3.38	23.53

Velocity and peak discharge values, estimated as the product of average velocity and the flow cross section area, are reported in Table 1. Velocities ranged from 2.9 to 6.3 m/s in the Tariqabad creek while peak discharge varied between 8.5 and 57 m^3/sec. The velocity range for main flow reach of Gulshan creek is 3.4 to 6.9 m/sec while discharge lies between 23 and 79 m^3/sec. It is clear from the results that Gulshan creek has more velocity and discharge compared to Tariqabad. High values of velocity and discharge at seventh section of Tariqabad creek (Fig. 6 and Table 1) are considered to be the local effects of the feeding channel (Fig. 2 and 6), while Gulshan creek has no tributary.

4. NUMERICAL SIMULATION

Given the threat that inhabitants along these creeks face, it is important to evaluate the debris flow risk and perform hazard zoning with the help of runout analysis. To achieve this goal, a runout analysis tool should be practical and should give satisfying results. In these days of powerful numerical solutions to problems of increasing complexity, a straightforward simulation of debris mass flows is certainly possible. However with limited input data from site investigations, Depth Average Material Point Method (DAMPM) is used herein as a practical numerical tool.

4.1. Depth Average Material Point Method (DAMPM) Model:

The model is based on the concept of modeling a debris mass as a group of material columns, following a simpler semi-empirical approach based on the concept of equivalent fluid, defined by Hungr, 1995, as shown in Fig. 7. The net driving force responsible for the flow of material consists of the tangential component of weight, the basal resisting force, *T,* and the tangential internal pressure resultant, *P* (Fig. 7c). The resultant pressure term, *P*, is described by the pseudo three-dimensional Druker-Prager model whose yield surface is assumed to circumscribe the Mohr–Coulomb yield surface expressed in terms of the material cohesion, *c*, and the angle of internal friction, φ. The basal resisting force is defined by the Voellmy bi-parametric model (Voellmy, 1955), owing to the fact that it gives the most consistent results with field measured data, as:

$$T = A\left\{\rho gh\left(\cos\alpha + \frac{a_c}{g}\right)(1 - r_u)\mu + \rho g\frac{\bar{v}^2}{\xi}\right\} \tag{4.1}$$

where A is the basal area, ρ is the bulk unit density of the column, g is the gravitational acceleration, h is the height of column, α is the bed slope angle, a_c is the centrifugal acceleration, dependent on the vertical curvature radius of the path, r_u is the pore-pressure coefficient (ratio of pore pressure to the total normal stress at the base of the column), μ is the basal frictional coefficient, $\bar{v}$ is the local depth-averaged velocity, ξ is the turbulence coefficient that describes the thickness of the basal layer, dilatant flow, viscosity and turbulence.

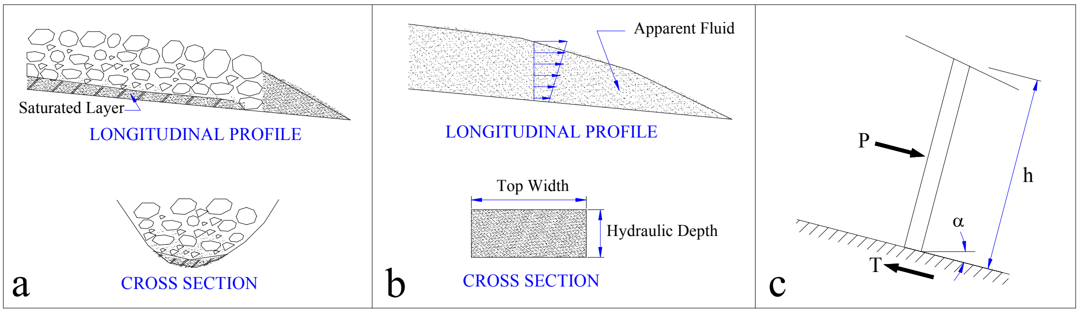

Figure 7. Basic concept of Depth Average Material Point Method (DAMPM) dynamic model a) prototype b) model c) forces acting on one column (after Hunger, 1995)

The model is based on discretization of St. Venant's depth-averaged equation of shallow open channel fluid flow, generalized for earth materials, with MPM (Material Point Method). MPM is a method proposed by Sulsky et al., 1994 to deal with large deformations, eliminating the mesh entanglement with all Lagrangian parameters assigned to material points which are updated at each time step. The governing equations and detailed numerical formulation is presented in Abe et al. (2007).

4.2. Calibration of Model

Important runout indications, which are measurable in situ or presumable from remaining traces, are the distal reach, velocity, flow thickness, deposit distribution and behavior in bend and at obstacles in the flow path. In this study first the effect of different input parameters of DAMPM is investigated on different runout features, and then the best fitted values are selected for the target area. The suitable ranges of important input parameters, for which the analysis has been carried out, are listed in Table 2 along with final calibrated/optimized values.

Table 2. Input parameters of the DAMPM dynamic model

Number	Input Parameters	Symbol	Unit	Suitable Range	Calibrated Values
1	Turbulence coefficient	ξ	(m/s^2)	500 – 1000	800
2	Sliding Friction	μ	--	0.06 - 0.12	0.06
3	Angle of Dilatancy	ψ	(deg)	0 – 12	0
4	Angle of internal friction	φ	(deg)	10 – 35	30
5	Cohesion	C	(Pa)	0 – 10	10
6	Material Density	ρ	(Kg/m^3)	1400 – 1900	1490

The parametric study and calibration is done for Gulshan creek (plan and sectional profiles are shown in Fig. 6 and 4, respectively). The Initial length, width and height for the debris mass were set at 24m, 12m and 1m, respectively, from topographical map and authors' observations during repeated field surveys. The element size and total number of material points were set to 2m and 594, respectively. The maximum, minimum and average envelopes of velocity and flow depth, used in the upcoming discussion, are calculated as maximum, minimum and average for all material pints, passing any point along the longitudinal distance. The final calibrated parameters are later tested for Tariqabad creek. The topographical settings are defined from detail GPS data while the domain outside the flow extent is modeled as a level area for simplification. For both the creeks, the y coordinate is a longitudinal distance along which flow takes place, with zero indicating the initiation point.

4.2.1. Effect of Turbulence Coefficient, ξ

Turbulence is the second term in the Voellmy model (Eqn. 4.1.), dependent on the square of velocity and density of debris, to summarize all velocity dependent factors of flow resistance. For the initial reach which is quite straight, the flow velocity significantly increases with the increased turbulence coefficient (Fig. 8a). Downstream of the point where the channel takes a sharp bend (Fig. 8a and 8b), this effect is not so significant because a lot of energy of the flowing mass is used up at the sharp bend and flow depth reduces significantly (Fig. 8b), resulting in reduced inertia. The channel bed gradient reduces gradually and falls below 5^o downstream of 700m longitudinal distance making the debris mass incapable of flowing further down with the presence in Eqn. 4.1. of Coulomb frictional coefficient of 0.1, and eventually, turbulence has no significant effect on distal reach. It is also noted that the increase of turbulence coefficient results in an increase in the flow depth, which is clearer beyond the 200m longitudinal distance. This part of the flow channel has more small curvatures than the initial reach. The centrifugal force and resulting superelevation are directly related to the square of velocity, giving a higher maximum envelop of flow depth for the higher value of ξ (Fig. 8b).

4.2.2. Effect of Frictional Coefficient, μ

Along the initial reach, the flow has minimum variation as compared to the relatively irregular profile downstream of the sharp bend (Fig. 9a and 9b). Concentration of material along the outer bank due to centrifugal effects increases the basal frictional area, making the effect of the frictional coefficient more pronounced while inertia and bed slope go on reducing gradually. This all results in reduced velocity with an increased frictional coefficient along the lower reach which confers a reduced distal reach. Along the lower reach with a flat gradient, material becomes incapable of flowing with increased frictional coefficient and starts accumulating, giving more depositional depth (Fig. 9b). A smaller value of frictional coefficient (e.g. 0.06) successfully simulates the flow of debris mass on the flat gradient downstream of 700m along the longitudinal distance with reasonable value of velocity.

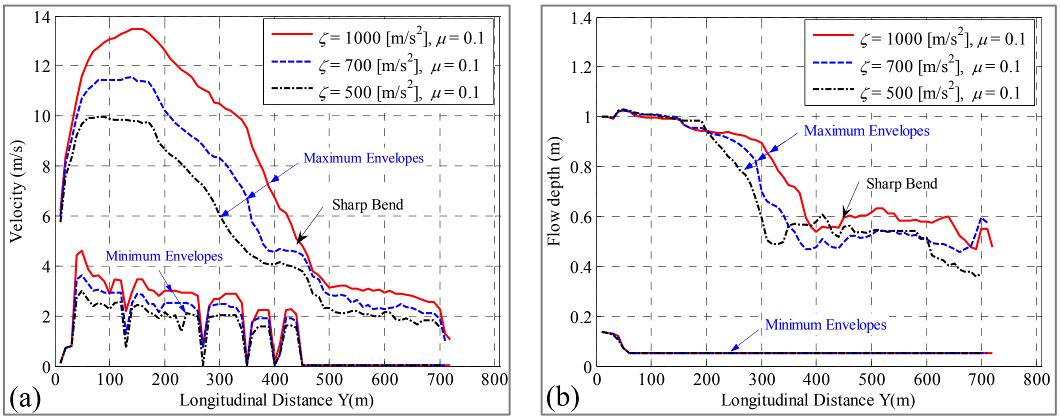

Figure 8. Effect of turbulence coefficient on a) flow velocity b) flow depth

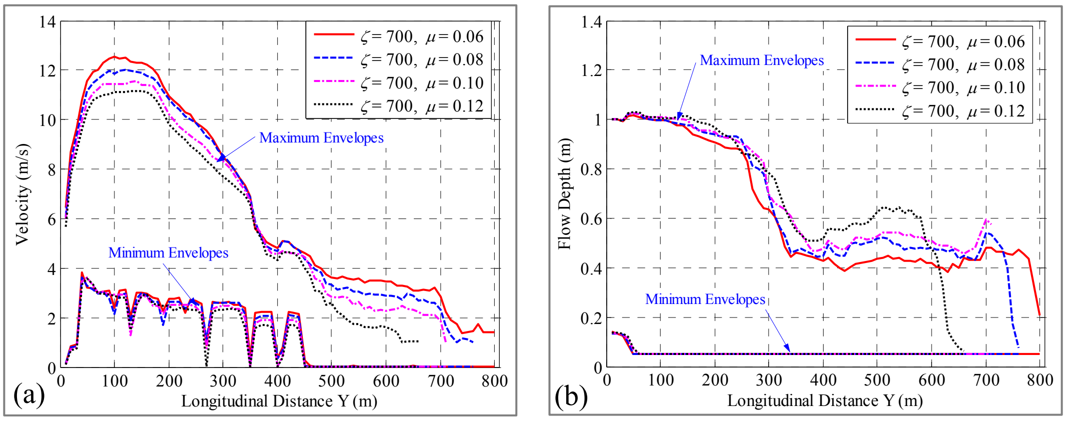

Figure 9. Effect of basal frictional coefficient on a) flow velocity b) flow depth

4.2.3. Effect of Dilatancy, ψ

Dilatancy seems to be one of the most important candidate input parameter controlling runout features. The flow width increases with an increased angle of dilatancy due to more lateral spread which results in reduced flow and depositional depth (Fig. 10b). This effect is very small along the initial reach which is almost straight, but prominent along irregular profile where material concentrates along the outer bank giving more space for lateral spread along the inner bank, depending on flow volume and flow cross section. This dispersion helps in reducing kinetic energy and at the same time it also gives an increased basal contact area, dominating the effect of the basal frictional coefficient and reducing velocity (Fig. 10a). The flowing mass has reached the investigated distance of the creek for all the cases but arrival time was different due to different flow velocities**.**

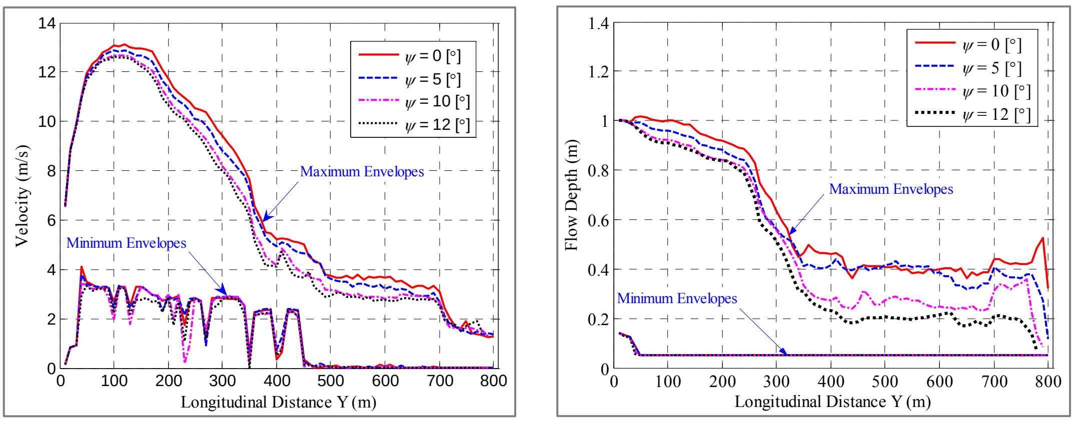

Figure 10. Effect of dilatancy on a) flow velocity b) flow depth

4.2.4. Effect of Angle of Internal Friction, φ

The angle of internal friction represents the strength of material against failure under applied pressure. Material with low strength (a small angle of friction) is capable of undergoing large planner deformation under increased pressure, and after fitting into the flow boundaries, is confined back in the center. This alternate lateral spread and confinement along with sudden change of plane and sectional profiles give fluctuation in maximum flow depth envelope for low strength material (Fig. 11b). The velocity of flow is not affected significantly (Fig. 11a).

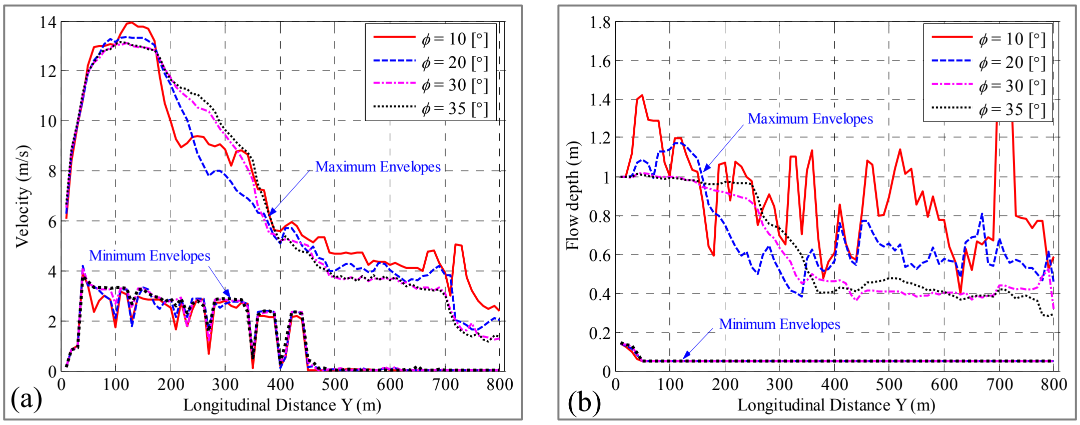

Figure 11. Effect of angle of internal friction on a) flow velocity b) flow depth

4.2.5. Effect of Internal Cohesion, C, and Mass Density, ρ

By analyzing for different values of cohesion and mass density, it has been found that both of these have almost no effect on runout features; however, it is found that with zero or a very small value of cohesion, material has much less damping and flows out of the flow track at sharp bends due to flow fluctuation. Depending on the topographical setting, this material may flow out of the computational domain resulting in instability of a numerical algorithm, as constant volume is the basis for updating the flow height at each time step. Therefore it is appropriate to work with some minimum value of cohesion (e.g. 10 Pa) even for straight torrent configuration. In terms of calibration, cohesion and mass density do not play a significant role in controlling runout features.

4.2.6. Verification of the Model against Measured Values

Fig. 12 shows results with the final calibrated parameters for Gulshan creek (see the rightmost column of Table 2). The initial thickness of the debris mass was set at 1m, which was verified from the backward erosion of loose material observed during the last field survey. The measured values fall well close to the average envelopes for velocity and flow depth normalized with the depth at the initiation section (at Y = 0 m).

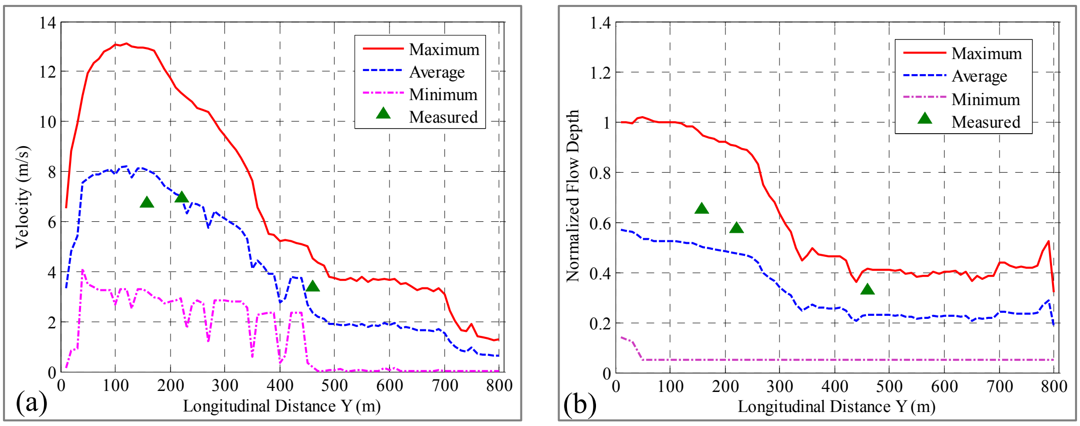

Figure 12. Simulation results with final calibrated input parameters along with measured values for Gulshan creek a) flow velocity b) normalized flow depth

To ensure validation of calibration work, these calibrated parameters are evaluated for Tariqabad creek. For Tariqabad creek, initial length, width and height of debris mass were set at 30m, 16m and 1m, respectively, equal to the area seemingly responsible for initiation of debris flow, observed during the field survey. While testing these parameters for Tariqabad creek, it was found that both measured flow depth normalized with depth at the initiation section and velocity agree well with the simulated values except for the seventh section (750m along longitudinal distance) where a confluencing channel makes all measured values significantly higher and this effect lasts to its downstream as well (Fig. 13).

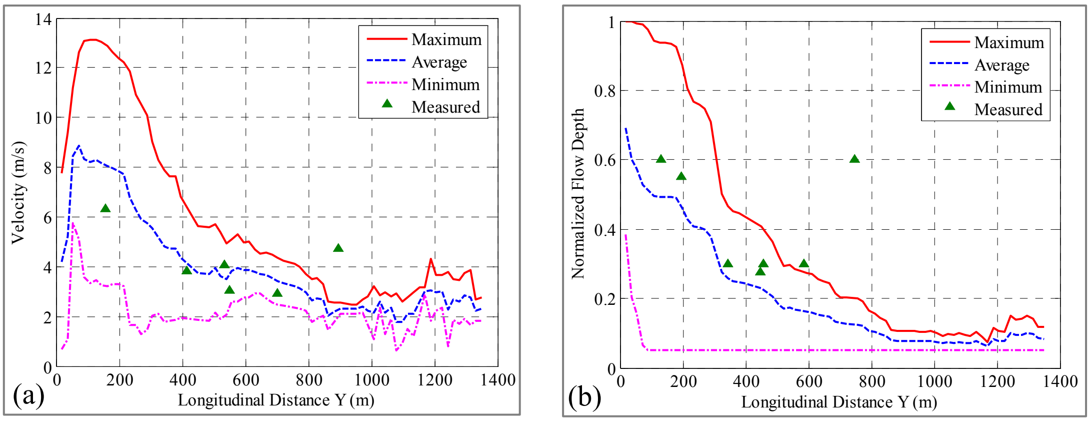

Figure 13. Application of the calibrated model to Tariqabad creek a) flow velocity b) normalized flow depth

5. CONCLUSIONS

A massive earthquake often causes long-lasting geological issues, and the October 8th, 2005 Kashmir Earthquake was no exception. Repeated field measurements are one of the most reliable ways to understand the behavior of real debris flows and to evaluate hazard levels for different areas. Debris flows along both the studied creeks followed the past experience for initiation, transportation, deposition and bed gradient. Any control structure/s or protection work/s cannot ensure complete elimination of risk from the mobilized debris flows. It is therefore necessary to know the hazard level by simulating runout features using a realistic and practical numerical model. Calibration of input parameters of a numerical model for given geological and topographical setting and knowledge of their physical effect is very important, and DAMPM has shown satisfactory correlation with measured values after calibration.

REFERENCES

Abe, K., Johansson, J. and Konagai, K. (2007). A new method for the run-out analysis and motion prediction of rapid and long-traveling landslides with MPM. *Journals of JSCE*. **Div. A, No. 63/I-1**, 1-17.

Ahmad, H., Yeast, R.S. and MonaLisa. (2009). Geological setting of the 8 October 2005 Kashmir earthquake. *Journal of Seismology*. **13:3**, 315-325.

Chow, V.T. (1959). Open-channel hydraulics. *McGraw-Hill, New York.*

Hungr, O. (1995). A model for the runout analysis of rapid flow slides, debris flows and avalanches. *Canadian Geotechnical Journal.* **32**, 610-623.

Johnson, A.M., Rodine, J.R. (1984). Debris flow. *D. Bnmsden & D.B. Prior (eds). Slope Instability, Wiley*. **Chapter 8**, 257-361.

Kumahara, Y. and Nakata, T. (2006). Active faults in the epicentral area of the 2005 Pakistan earthquake. *Research Center for Regional Geography, Hiroshima University, Japan*. 54pp.

Sato, H., P., Hasegawa, H., Satoshi, F., Tobita, M., Koarai, M., Une, H. and Iwahashi, J. (2007). Interpretation of landslide distribution triggered by 2005 Northern Pakistan earthquake using SPOT 5 imagery. *Landslides*. **4:2**,113-122

Sulsky, D., Chen, Z., Schreyer, H. L. (1994). A particle method for history-dependent materials. *Computer Methods in Applied Mechanics and Engineering*. **118:1**, 179-196.

Voellmy, A. (1955) Über die Zerstorungkraft von Lawinen. *Schweiz Bauzeitung*. **73**, 212-285.