SLOPE FAILURE INDUCED DEBRIS FLOW HAZARDS IN THE OCTOBER 8, 2005, KASHMIR EARTHQUAKE

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ABSTRACT: A devastating earthquake occurred in Kashmir, Pakistan on October 8, 2005. This earthquake is resulted from reactivation of known active fault later defined as Balakot-Garhi fault which caused widespread slope failure throughout its stretch, particularly around Muzaffarabad. This slope failure resulted in a huge amount of debris material which flows in incised nallahs (channels) during monsoon and hits the inhabitants in the valley along Muzaffarabad. Two GPS surveys, June 2008 and November 2008, have been carried out to investigate the effect of debris flows along these nallahs. During second survey, morphometric parameters of channels and some physical characteristics of the flowing material were also measured. Using the GPS measurements as elevation data for the study area, the actual debris flow is simulated using numerical code based on DAMPM (Depth Average Material Point Method). This paper briefly highlights the findings obtained form repeated field measurements and from the simulation of the actual flow.

Key Words: Kashmir earthquake, Balakot-Garhi fault, debris flow, nallahs, Depth Average Material Point Method

INTRODUCTION

The October 8, 2005 Kashmir earthquake occurred at 08:50 (03:50UTC) local time of Pakistan at 34.493°N, 73.629°E, about 10km NE of Muzaffarabad and 105km NNE of Islamabad (USGS). The earthquake was of moment magnitude 7.6 (Mw) and focal depth is fixed at 26km (USGS). This was the deadliest earthquake in South Asia's recent history, with >86000 fatalities, > 69000 people injured, >32000 buildings destroyed and 4 million people left homeless. The largest city affected by the earthquake was Muzaffarabad which is the capital of Azad Kashmir, a self governing state administrated by Pakistan.

The earthquake occurred as a result of reactivation of known thrust faults stretching from Balakot to Bagh with surface rupture observed at very few locations (e.g. at Bagh reported by Geological Survey of Pakistan). Using satellite data and fault modeling, various researchers [e.g. Hiroshi P. Sato et al., Geographical Survey Institute (GSI), Japan] found that high crustal deformation has occurred along the known active faults stretching northwest and southeast from epicenter [Nakata et al. 1991], with northeastern part moved upward. These known active faults are divided into two groups, the

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Muzaffarabad fault (northwest of Muzaffarabad) and Tanda fault (southeast of Muzaffarabad) [Nakata et al. 1991]. Recently, Kumahara and Nakata (2006) gave a redefinition of Tanda fault and Muzaffarabad fault, and they comprehensively renamed them as Balakot-Garhi fault.

This earthquake triggered thousands of landslides and slope failures including debris slides and debris flow throughout the region, causing about one third of total fatalities, destroying roads and disrupting communications. Most failures were shallow, typically involving the top few meters of the weathered rock, regolith, and soil. Many of these failures are still active and loose fractured material is moving down the steep slopes even under the gravity. This failure is present all along the active fault but most serious around Muzaffarabad city for its extent and long lasting problems (**Fig.1**). The failure

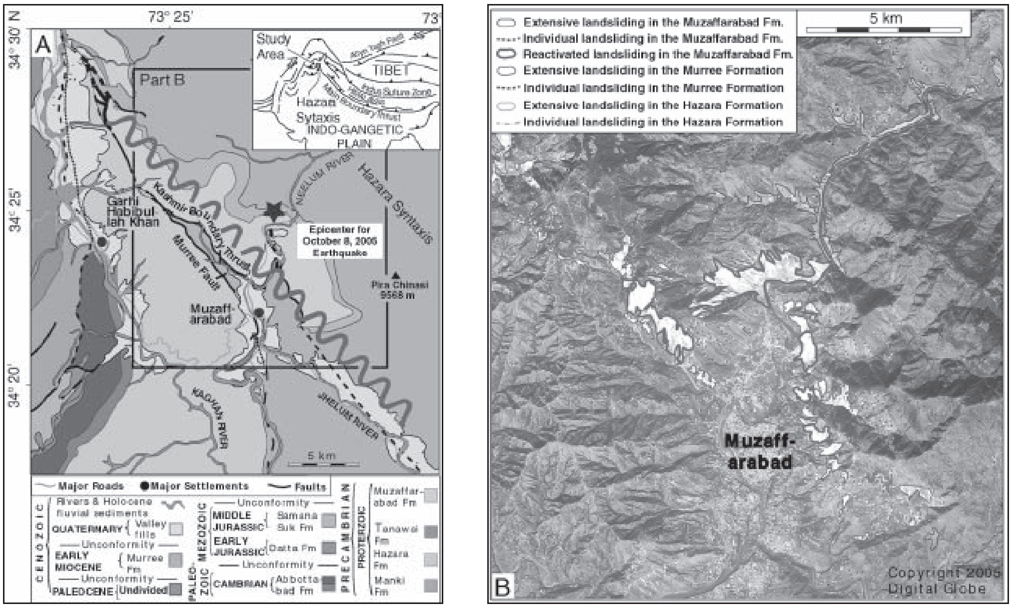


Fig.1 A) Simplified geological map of the area around Muzaffarabad and **B)** Quickbird image showing region of most extensive slope failure: Red wave indicates area of maximum crustal deformation (after Geological Survey Institute, 2006; Avouac et al., 2006).

occurred in Muzaffarabad Formation, which forms steep valley slopes, many>50^{o} above the main rivers of the alluvial and valley fills. The Muzaffarabad Formation comprises thinly bedded and highly fractured dolomite constituting the lower beds in the hanging wall of Balakot-Garhi fault. This fractured loose material is a big source of debris flow with favorable conditions for the phenomena to occur. **Fig.2** shows average rainfall data at Muzaffarabad from 2005 to 2008.

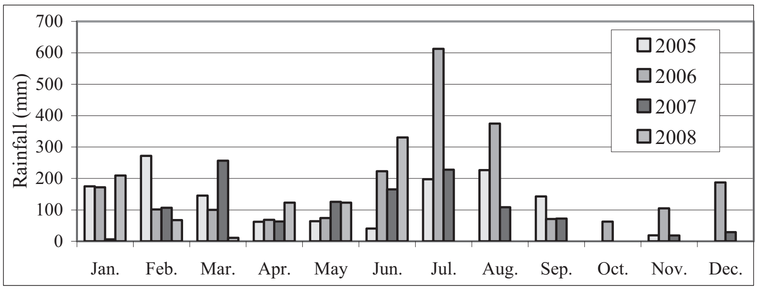
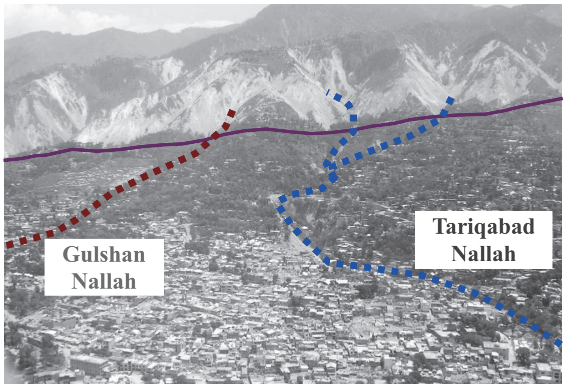


Fig.2 Monthly average rainfall at Muzaffarabad (data from Pakistan meteorological department)

The available data and district census report, 1998 suggests monsoonal climate with an average annual precipitation of about 1510 mm, with a major portion falling as rain during the monsoon season (June-August). At higher altitudes (above 1500m asl), precipitation falls as snow during the winter (December to March). The mean maximum and minimum temperature at Muzaffarabad are 16°C and 3°C during winter (January) and 38°C and 22°C during summer (June), respectively (District Census Report, 1998).

STUDY AREA

The causative Balakot-Garhi fault passing just behind the Muzaffarabad city, with city on its footwall, caused a widespread linear slope failure, with a huge amount of highly sheared and fractured loose material exposed (**Fig.3a**). During heavy rains of monsoon, this loose material combined with water moves as debris flows in the deeply incised nallahs (Urdu word used for channel) and hits the inhabitants. These nallahs directly pass through the Muzaffarabad city and feed the Neelum river flowing southward immediately at the western end of the city. People living in the valley along these nallahs are seriously effected by the debris flow with there houses half or full buried (**Fig.3b**). We selected two most damaging, Gulshan and Tariqabad nallahs (**Fig.3a**) passing through highly populated valley of Muzaffarabad city and carried out GPS measurements at two different times, June 2008 and November 2008, measured channel morphometric parameters and observed the changes. Processing the GPS data to formulate digital elevation data of the target area, flow is simulated for Gulshan nallah to understand actual flow behavior and damage distribution.



(**a**) Debris sources exposed behind Muzaffarabad

(**b**) Houses half buried in debris

Fig. 3: Debris deposit from activated fault in Kashmir (Muzaffarabad): Purple line show the causative fault (Balakot-Garhi fault) of Kashmir Earthquake

GPS MEASUREMENTS

Two GPS measurements were taken enclosing the monsoon season to investigate the behavior and effects of debris flows in Gulshan and Tariqabad nallahs. The differential GPS system is used with one system installed at the fixed reference point (at the roof of DAM office), while the others worked as kinematic station taking measurements at a number of points marked along the selected nallahs (**Fig.4a** and **4b**). The system also marks the points automatically at an interval of one second but the accuracy is not as high as that of marked points due to non-verticality of antenna pole and very short acquisition time. Two types of measurements are taken, one along the lowest point in the nallah to investigate the nallah bed erosion and deposition and the other at three different points to define the flow cross sections (**Fig. 4b**). The outer flow boundaries are found from available traces of debris material or mud marks. This also gives an idea about the erosion and deposition along the banks of nallah and change in flow width.

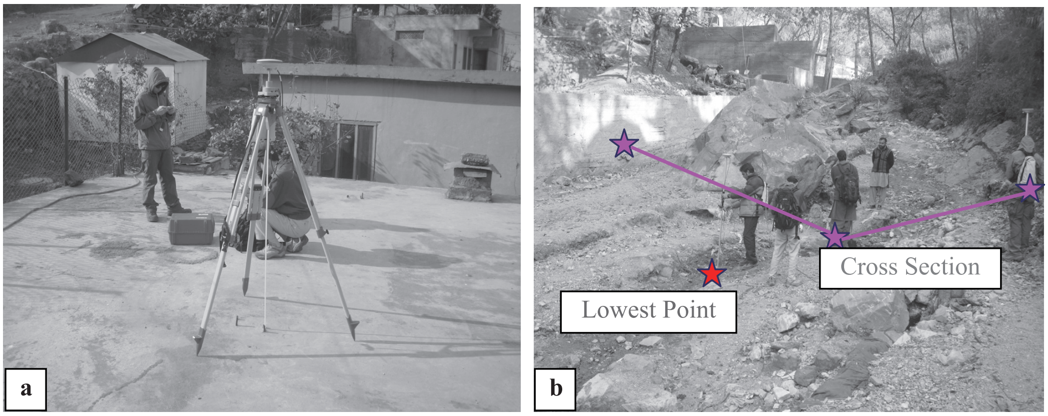


Fig. 4: GPS measurements along Gulshan and Tariqabad nallahs **a)** fixed reference station at roof of DAM office **b)** measurement for lowest point and cross section

The points marked along both the nallahs during two surveys do not lie exactly above each other. Therefore, all the measured points are transferred to a common projection plane for the comparison and investigation of nallahs bed erosion and deposition. The common projection plane is actually a combination of least square lines, each for certain group of points following certain trend. **Fig.5** shows the plan profile of both the nallahs, showing all the marked points along with the common projection plane. The detail erosion deposition analysis and other observations are explained in the following sub-sections separately for each nallah.

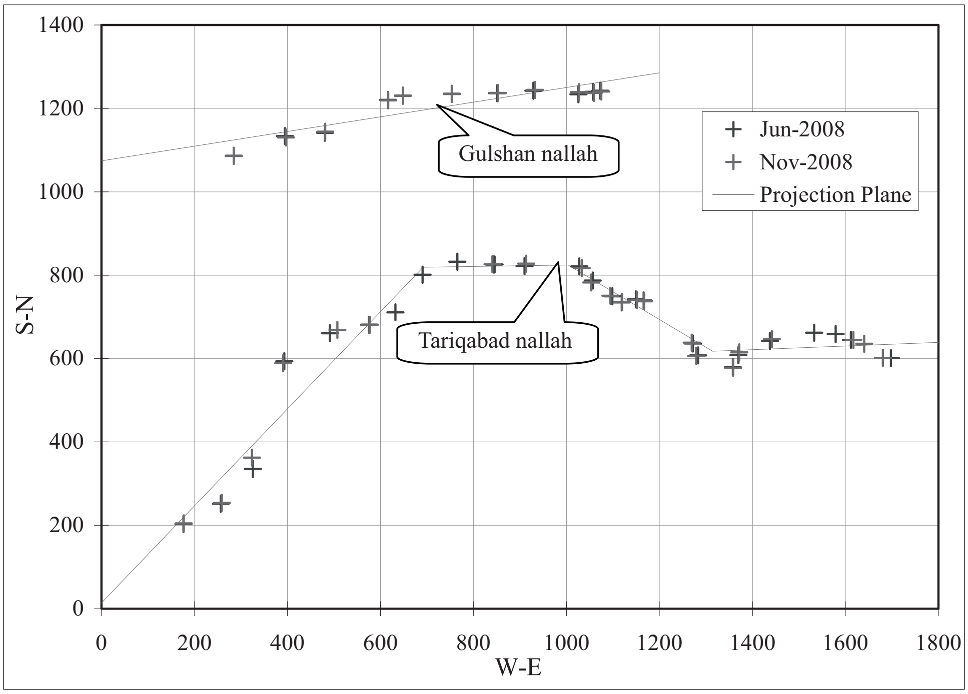


Fig. 5: Profiles of Gulshan and Tariqabad Nallahs along with a common projection plane

Gulshan Nallah

Gulshan nallah has a total length of about 900m with quite straight configuration. Since June and November measured points do not mach exactly by location in the elevation plot (**Fig.6)**, therefore curves are fitted to the marked data points by curve fitting technique using *spline* cubic function (**Fig.6).** The measured data points were divided into a number of groups following certain trend for smooth curve fitting. Even then this curve fitting may involve some error and gives an assumed profile between two measured points, but is a way to quantitatively evaluate erosion and deposition. By taking June measured points with fitted curve as reference, due to higher accuracy of June measurements, erosion and deposition analysis is carried out along the entire length of nallah.

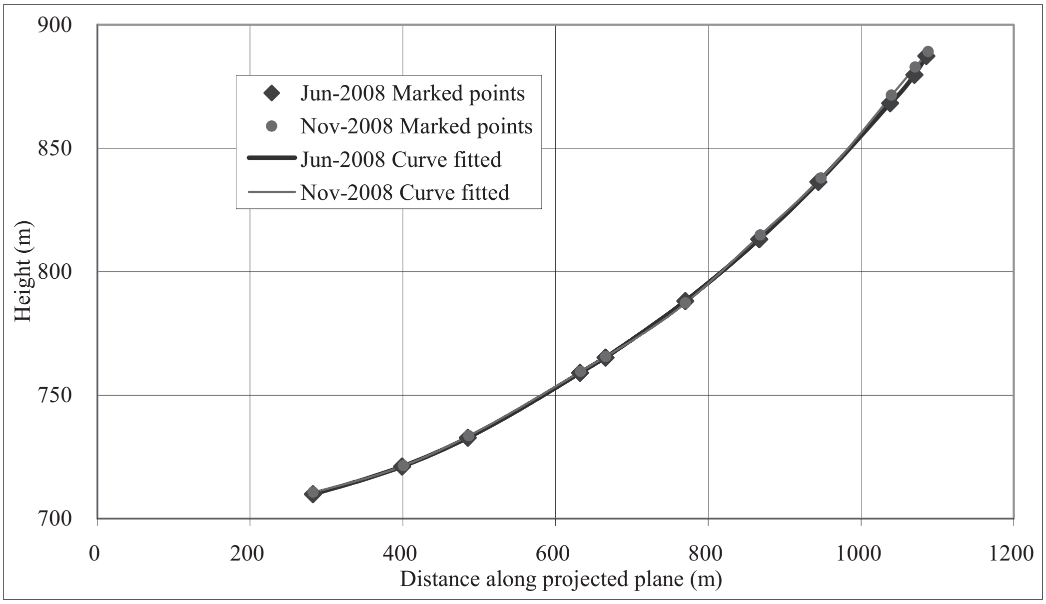


Fig. 6: Plot of June 2008 and November 2008 measured data points with curves fitted using cubic *spline* function

Fig. 7(a) shows the elevation changes of November measured points with reference to curve fitted to June measured data while **Fig.7(b)** shows the comparison of curves fitted to the both measured data indicating erosion and deposition along the total length of nallah with reference to the curve fitted to June measured data. In both of these figures, 7(a) and (b), negative values indicate erosion while positive values indicate deposition. **Fig.7(c)** shows the nallah bed gradient computed both from detail curve fitted data and measured points. The length above the point of 1000m along projected plane is the initiation zone with a bed gradient of $\geq 20^{o}$, verified by repeated field surveys. Very high depositional depth of about 3m shown in this zone is the accumulation of loose fractured material from the steep catchment of nallah which is then mobilized by rain water. Downstream of the point of 670m along the projected plane, data shows deposition along the channel with a gradient of $\leq 10^{o}$ defining the deposition zone. Data shows a depositional depth upto 0.9m with less depth at some places where material has been removed by local people for their use. Between these two points, both erosion and deposition have occurred defining the flow and transportation zone with the bed gradient between 10^{o}-20^{o}. Erosion and deposition in this reach well agrees with the bed gradient variation with steep gradient responsible for erosion. This closely agrees with literature based on past observations in different areas of the world. Inhabitants are mostly populated in the depositional zone suffering from repeated debris flow events during monsoon.

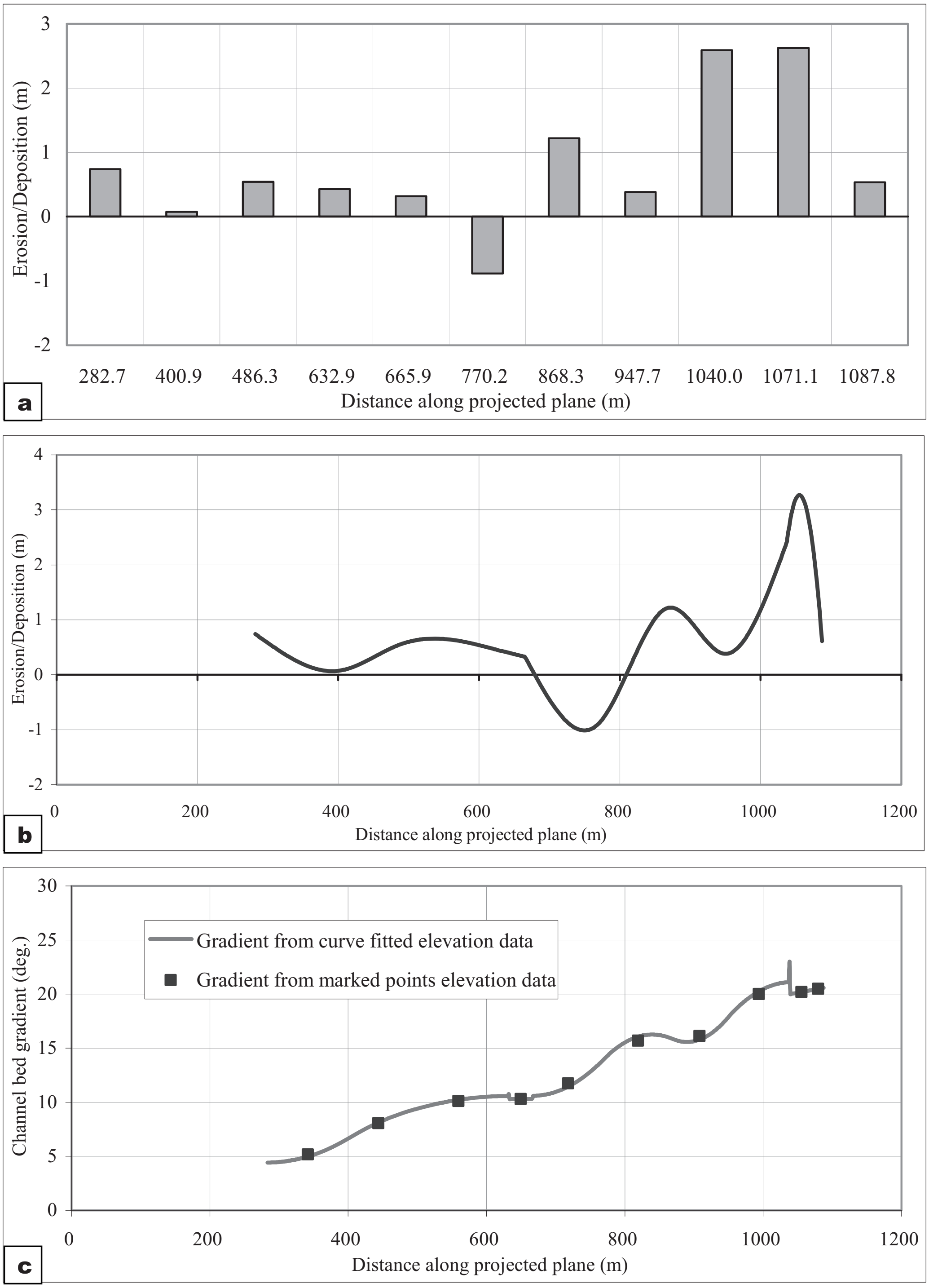


Fig. 7: a) Elevation changes of November measured points with reference to curve fitted to June measurement **b)** elevation changes along total length of nallah from curve fitted data **c)** nallah bed gradient

Tariqabad Nallah

Tariqabad nallah has a total length of about 1900m with an irregular configuration. Due to mismatching location of June and November measurements (**Fig.8**), curves were fitted using cubic *spline* function to the measured data points (**Fig.8**). Due to complex configuration of Tariqabad nallah, measured data points were divided into about 10 groups each following certain trend for smooth curve fitting. This curve fitting gives assumed profile of elevation between two measured points and may involve some error but makes quantitative evaluation possible. By taking June data as reference, erosion and deposition analysis is carried out along the nallah bed. **Fig.9(a)** shows the elevation changes of November measured points from curve fitted to June measured data while **Fig.9(b)** shows detail erosion and deposition comparing the curves fitted to measured data (negative values indicate erosion) with nallah bed gradient shown in **Fig.9(c)**. The length of nallah above point of 2000m along the projected plane is responsible for the initiation of the debris flow with a bed gradient of $\geq 18^{o}$.This reach has very steep channel banks with highly fractured loose debris material. This material flows down the steep slopes and is accumulated in nallah from where it is transported by already mobilized debris mass little upstream of it. GPS data indicates erosion in this reach which is the transportation of accumulated material and takes time to accumulate again. Downstream of point of 875m along projected plane, data shows deposition along the channel with a gradient of $<10^{o}$ defining the deposition zone. Depositional reach is relatively long with more depositional depth as compared to Gulshan nallah. This may be attributed to long length, irregular configuration and tributaries feeding at lower reach of nallah. Some points in this depositional zone indicate erosion which is resulted by man made changes and excavation of deposited material, observed during survey. Between both of the above mentioned points is 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^{o}-18^{o} with some local high values.

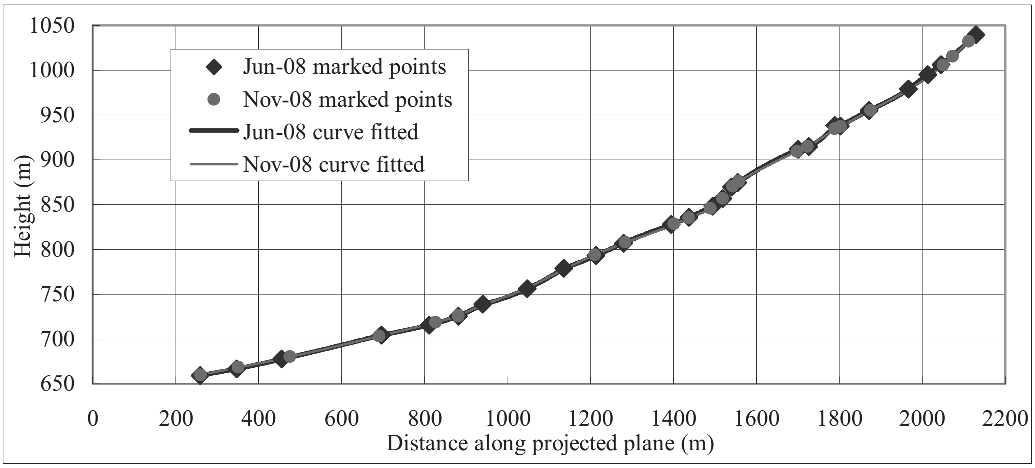


Fig. 8: Plot of June 2008 and November 2008 measured data points with curves fitted using cubic *spline* function

Inhabitants are mostly populated in the depositional reach with some living along the lower portion of flow and transportation zone. Due to irregular configuration of nallah, flow concentrates to outer sides of bend sections resulting in under cutting of outer bank. This undercutting causes landslides along the steep banks which is vital for inhabitants and some communication structures to considerable range. Such landslides inside the nallah are another source of debris material and are much dangerous due to bursting phenomena of temporary dams which they create.

Fig. 9: a) Elevation changes of November measured points with reference to curve fitted to June measurement **b)** elevation changes along total length of nallah from curve fitted data **c)** nallah bed gradient

Fig.10 shows the change of flow width obtained from the measurements taken at the outer flow boundaries defined by traces of debris material or mud marks. Due to mismatching of marked points during two surveys, the detail comparison is quite difficult but the increased flow width in initial zone is evidences transportation of material accumulated in the nallah from steep banks. Decrease in flow width is possible with the disturbance of flow boundaries by nature or human activities. Depositional reaches of nallahs are usually disturbed by local people by removal of material for their use or by construction of some structure. This is quite clear that downstream of point ***A*** in figure 10, which is the populated zone, flow depth has more disturbances as compared to upstream of that

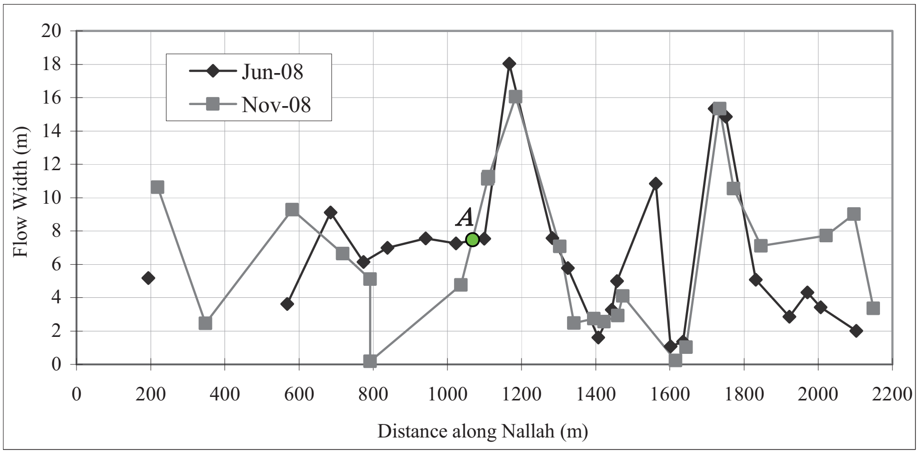


Fig.10 Channel flow width

CHANNEL MORPHOMETRIC PARAMETERS

During the second survey, 11 cross sections of both the nallahs were measured at bends (**Fig.11** and **Table1**). At these sections with channel slope less than 15°, the velocity of debris flow was estimated from superelevation of lateral deposits or mud lines left by the peak discharge according to Johnson (1984) as;

$$v^2 = g \times \psi \times \Delta h / W$$

Where *g* is the acceleration due to gravity, ψ is the radius of curvature of centre line of channel bend, Δh is the superelevation of flow and *W* is the flow width.

Due to quite straight configuration of Gulshan nallah, available numbers of sections for measurement were less compared to Tariqabad nallah. In the field superelevation angle of lateral deposit was measured by clinometer, cross section was measured with tape and radius of curvature was determined from the automatically marked points by GPS at an interval of one second. 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 4.8 to 10 m/s in the initiation and flow zones of Tariqabad nallah and about less than 4.0 m/s in the depositional reach. Debris flow peak discharge varied between 21 and 90 m^3/sec. The velocity range for main flow reach of Gulshan nallah is 5.3 to 6.9 m/sec while discharge lies between 37 to 76m^3/sec. The depositional reaches of both the nallah are usually disturbed by removal of deposited material for local use. It is clear from the results that Gulshan nallah has more velocity and discharge compared to Tariqabad nallah. The first and 7th sections in Tariqabad nallah show high values of velocity and discharge which are local effects of feeding channels while Gulshan nallah has no tributary.

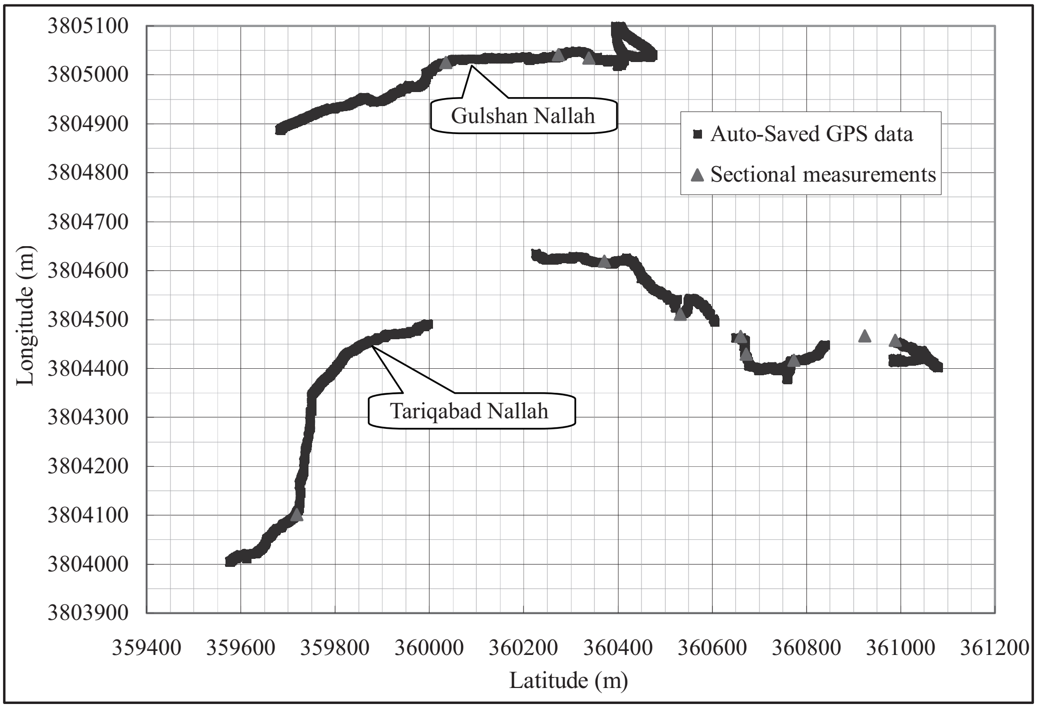


Fig.11 Auto marked GPS data showing profiles of nallahs along with sections of velocity and discharge measurement

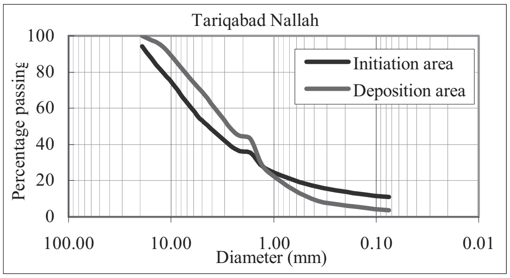
Table 1 Morphometric measurements along Gulshan and Tariqabad nallahs

Nallah	Section #	Depth *D* (m)	Width *W* (m)	β (°)	*Ψ* (m)	*v* (m/sec.)	Q (m^3/sec.)
Tariqabad	1	1.20	3.30	11	52.38	9.99	39.58
	2	1.25	3.10	7	N/A	N/A	N.A
	3	0.63	8.50	4	53.57	6.06	32.20
	4	1.15	5.60	6	40.48	6.46	41.60
	5	1.65	4.30	8	16.67	4.79	34.01
	6	1.05	5.10	6	15.48	3.99	21.39
	7	1.20	10.00	5	65.48	7.50	89.96
	8	N/A	12.00	3	45.24	4.82	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	5.35	37.21

Inverson at el. (1994) analyzed the error involved in the superelevation method and found estimates to be within 30% of measured velocity values, with error mainly due to the passage of frontal bore in which conditions of steady and uniform flow are violated, particularly at sharp bends. Moreover splashing at the bends could exaggerate mud marks, and assumption of linear surface profile may overestimate the flow cross section (Jakob et al., 1997).

MATERIAL PHYSICAL CHARACTERISTICS

Grain size distribution has been performed on material sampled in deposition and source area. The grain size distribution, obtained on the fraction passing 20mm sieve, shows a difference between two areas (**Fig.12**). While flowing from initiation to deposition area percentage of fines (less than about 1 mm) is decreased but the fraction ranging from 1-20mm has significantly increased in both the nallahs. High shearing effect at the initiation area due to the fault may have caused extremely fine particles which may have washed during flow or flowed down the depositional reach as hyperconcentrated flow. But the sand size particles are increased due to the rolling and collision effect as well due to entrapping the bank material which consists of Murree formation having a good fraction of sand size particles.



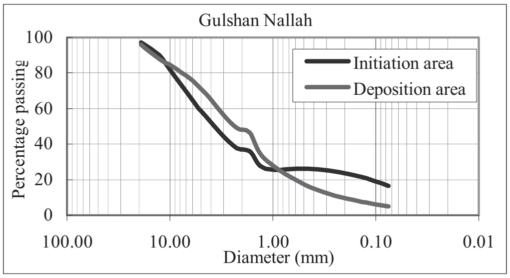


Fig.12 Grain size distribution of source and deposited material in Gulshan and Tariqabad nallahs

NUMERICAL SIMULATION

Though many erosion protection and mass flow control structures are being used to reduce the devastating effects of debris flow but still the hazard is there because the complete control of flowing masses is not possible. Thus it is important to evaluate the debris flow risk and perform hazard zoning with the help of run-out analysis and the contribution of any control structure in hazard reduction to its downstream. Also it is very important to understand the actual flow behavior for certain material and topographical settings.

To achieve the above mentioned goals, run-out analysis tool should be practical and should give satisfying results with limited input data from site investigations. For the subject study DAMPM (Depth Average Material Point Method) numerical tool is used. MPM (Material Point Method) is method proposed by Sulsky et al. (1995) to deal with large deformations, eliminating the mesh entanglement. In this method, the Material Points carry all the lagrangian parameters which are updated at each time step and more realistic constitutive models (Drucker-Pragar Model) can be implemented. In DAMPM, modeling a debris flow mass as a group of material columns, following a simpler semi-empirical approach based on the concept of equivalent fluid, defined by Hungr (1995), is implemented in MPM for run-out analysis across three dimensional terrains. The practicality of the tool is proved by Abe et al. comparing the computational results with that of experimental results of open flume experiment performed by Denlinger et al.

Modeling

GPS detail measured data along Gulshan nallah is processed to formulate the digital elevation data of the target area defining the topographical setting. The domain outside the flow extent is just modeled as level area. The debris flow mass is modeled as a cluster of material columns. Some of the input parameters are tried to be adjusted to reproduce the close approximation of actual flow, observed during survey, while other taken as Abe et al. used in comparison of computational and experimental results.

The simulation results showing the flow depth and velocity distributions along the entire nallah are shown in **Fig.13** and **14** respectively. Color bars show the magnitude of the flow depth and flow velocity while solid lines in the figure are elevation contours showing three dimensional terrain in two dimensional setting (Pseudo 3D). Flow behavior (e.g. concentration of flow at outer edges of bend sections and front bore having high velocity) can also be observed from these animations. Computational parameters used as input for these animations are summarized in **Table2**.

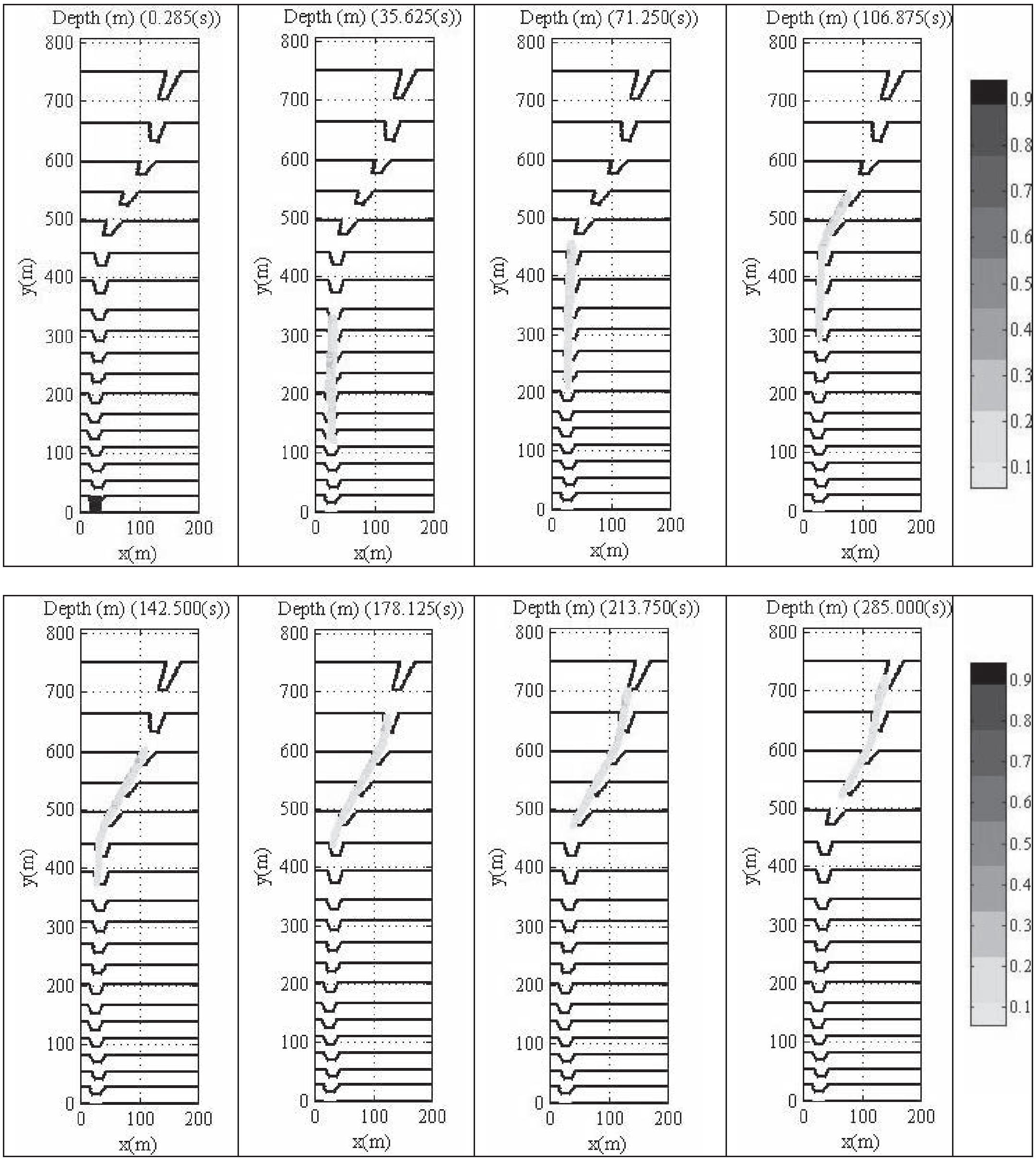


Fig.13 Flow depth distribution and flow behavior along the entire reach of Gulshan Nallah

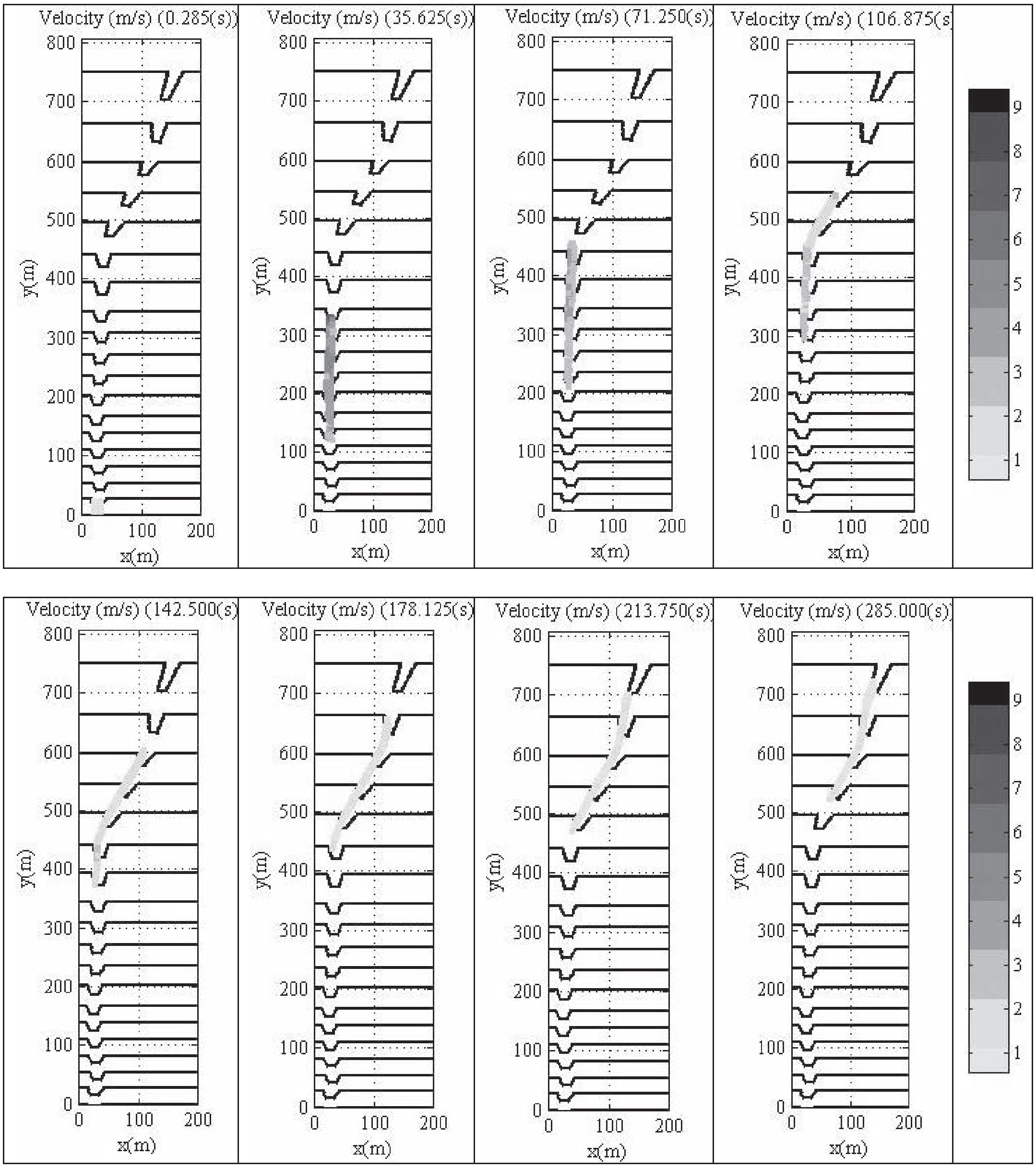


Fig.14 Velocity (in the direction of flow) distribution along the entire reach of Gulshan Nallah

Table 2. Input parameters used for Gulshan Nallah

Basal friction angle	5.7 (deg)	Angle of dilatancy	0.0 (deg)
Internal friction angle	30 (deg)	Number of material points/cell	9.0
Density	1590 (kg/m^3)	Length of mesh	2.0 m
Young's modulus	2.10×10^6 (Pa)	Turbulence coefficient	700 (m/sec^2)
Poisson's ratio	0.30		

Fig.15 shows the distribution of flow depth and flow velocity along the nallah along with the measured values by superelevation method. Both measured and simulation flow depth values are normalized with the flow depth at initiation section. The average flow velocity and normalized flow depth values by simulation are comparable to measured values except at section 3 where excavation of deposited material may have resulted in increased flow depth during measurement. For further calibration one should concentrate on these input parameters but should notice that measured values also involve an error upto 30% due to passage of front bore (Inverson at el., 1994). During the field investigation, authors found that downstream point *A* population has almost converged inside the nallah and it is very important to control debris upstream of this point by providing control structure/s. Upstream from point *A*, point *B* gives the least envelop with respect to maximum flow depth and maximum velocity suggesting an optimized location for any control structure.

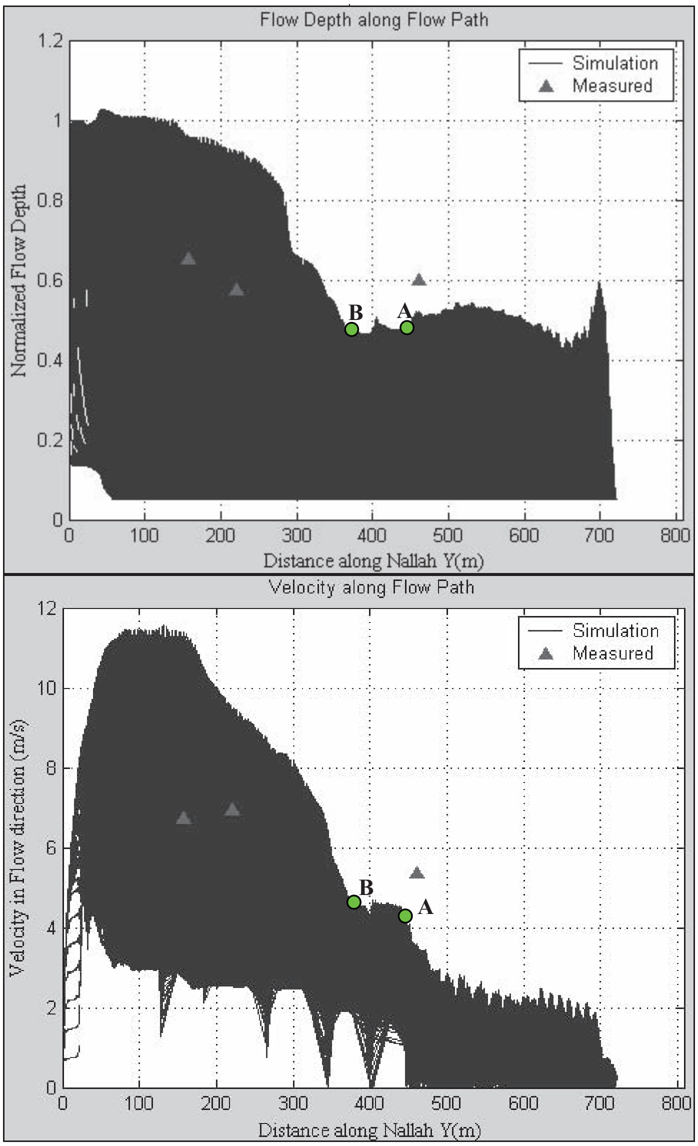


Fig.15 Flow depth and velocity distribution showing maximum and minimum envelops along with measured values

CONCLUSIONS AND COMMENTS

1. A massive earthquake often causes long-lasting geological issues, and the October 8, 2008 Kashmir Earthquake was no exception. To quickly cope with these problems, a detail study is quite necessary.
2. The debris flows along both the studied nallahs follow the past experience for initiation, transportation and deposition and bed gradient. The debris flow effect along both the nallahs to inhabitants is rather depositional than impact.
3. Repeated and detail field measurements help in understanding the true behavior of debris flow and allow the estimation of hazard for different areas.
4. Although the structural and erosion control measures are used for debris flow control but it is almost impossible to completely stop the phenomena and totally trap the debris. Therefore, it is quite realistic to know the extent of debris flow target and prepare the hazard zoning. This can be done by simulating the debris flow for maximum possible discharge using some numerical tool. But this is very important that numerical tool should give realistic behavior and should be much practical requiring least possible input.
5. Instead of providing the control structures blindly, it will be more efficient and economical if the control structure is decided at the optimized location which is the location at which the flow as minimum energy.
6. DAMPM gives close approximation of actual flow behavior. However the some discrepancy is due to change in material properties during flow and pore pressure which is not accounted for.

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