A QUANTITATIVE APPROACH TO ASSESS LANDFORM CHANGES OF HATTIAN BALLAH LANDSLIDE DAM FORMED BY 2005 KASHMIR EARTHQUAKE

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ABSTRACT:
A huge landslide triggered by Kashmir 2005 earthquake blocked the Karli and Tang branches of Jhelum River and formed two land slide-dammed lakes with larger being of volume 62 million m^3. The location of landslide dam is region of active landslides which predates the 2005 earthquake. An outburst flood now threatens the downstream areas and Muzaffarabad city. A quantitative approach of GPS measurements of landslide mass body indicates excessively large settlements and northwestward in-plane movement of whole dam body. Slaking, the resulting consolidation and washout process at surface are also components of resulting deformations. Isotopes study indicates seepage still from shallower coarser part of debris mass as initially assessed from seepage and water level measurements of lakes. Continual monitoring of landmass and potential landslide masses at critical stability on banks of large lake is essential for hazard assessment, risk awareness and preparedness in case of flood outburst.

Key Words:
Hattian-Ballah; Rock Avalanche; Landslide dam, GPS measurements; Quantitative approach, Kashmir Earthquake, Isotopes, Landform changes

INTRODUCTION

The October 8, 2005 earthquake of magnitude 7.6 (Mw) (US Geological Survey) with epicenter (34°29’35”N, 73°37’44”E at focal depth 10km) some 95 km from Islamabad caused widespread destruction in Kashmir and other northern areas of Pakistan. Landslide dams usually form in mountainous areas of high terrain (Costa and Schuster, 1988), where there are proper conditions for preparation (high hills-slope gradients and discontinuities such as bedding, faults, joints) and triggering factors of slope failure (Korup, 2002). In addition to widespread destruction to cities another major event during earthquake, was the formation of a huge landslide dam comprising 85 million m^3 which buried the Parhore valley (Owen, 2008) and blocking the waterways of the Karli and Tung tributaries of the Jhelum River. The landslide alone killed more then 1000 people equivalent to 1.1% of total earthquake fatalities, and 3.7% of the deaths caused by landslides; making it one of the most devastating recorded historical landslide events (Dunning, 2007). Failure of landslide dams usually results in catastrophic downstream flooding causing loss of life, housing and infrastructures. The Raikhot landslide dam of some 200–300 m in height which impounded a 65-km-long lake on the Indus River, Pakistan collapsed in 1841, which was the largest damming by landslide and resulting catastrophic flood that has been documented in the world (Duman, 2008). Some 200 km south of Raikhot is the huge Hattian-Ballah landslide mass posing a similar flood hazard to the downstream

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area including Hattian village and Muzaffarabad city. The major concerns are the stability of landslide mass itself and the evaluation of the surrounding unstable slopes which are threat to impounding large lake of volume 62 million m^3 (Schneider , 2008) which can eventually breach the landslide mass. However, literature regarding landslide dams is mostly of qualitative nature because of lack of observations during formation and failure events of these landslide dams, therefore making the evaluations difficult. The authors have been observing the landslide mass from time to time since its formation. Our research team initiated one of very few of its kinds, the quantitative approach for Hattain-Ballah landslide dam. Two surveys were conducted one in June 2008 and other one in November 2008 for GPS measurements over the landslide mass and collection of water samples for isotopes measurements of waters in impounding lakes and overflowing spillways. This report presents the data and results of GPS surveys, isotopes measurements, and there relation to landform changes scenarios of landslide mass till November 2008.

GEOLOGICAL SETTING OF 2005 KASHMIR EARTHQUAKE

The 2005 earthquake was a result of subduction of Indian Plate under the Eurasian plate. Fault solution shows that the earthquake was due to trusting causing a slip of maximum 9m and maximum uplift of 6m of area north of Muzaffarabad, (GSJ, 2006). It was the largest historical earthquake on the Indus-Kohistan Seismic Zone (IKSZ) and the first Himalayan earthquake to be accompanied by surface rupture, reactivating the Tanda reverse fault and locally offsetting the Main Boundary thrust (MBT) (Ahmad, 2008). The cities of Muzaffarabad, Bagh and Balakot were extremely damaged which lie along the Jhelum fault (Fig. 1). A total of 1778 after shocks were recorded northwest (continental convergent zone) of Muzaffarabad at the end of 2005 (Pakistan Metrological Department, 2006). Hattian-Ballah landslide dam lies at the southern end of the Tanda fault some 33km south east of Muzaffarabad and 3.4 km from Tanda fault. The source area of landslide is formed of Miocene aged Murree formation mudstones and sandstones (Fig. 2) with minor amount of limestone on hanging wall of Tanda fault (Dunning, 2007).

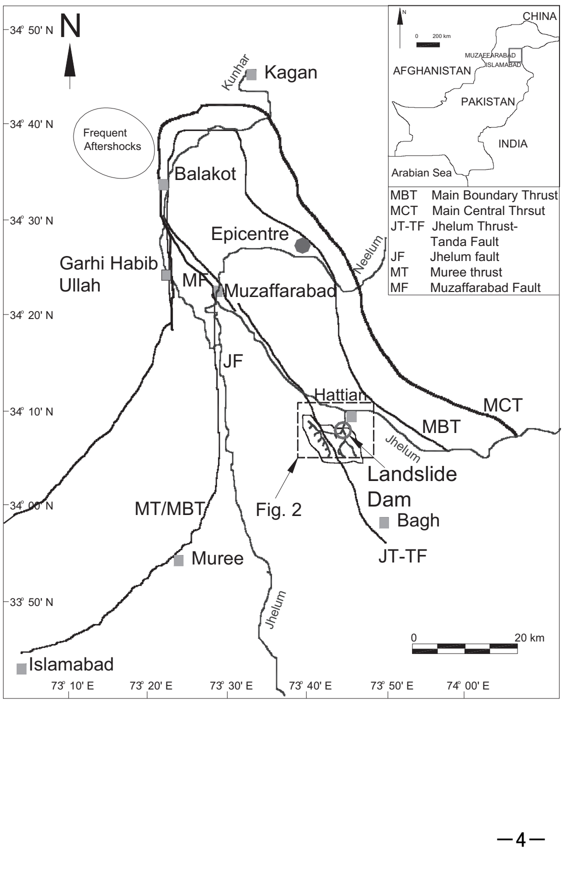


Fig. 1. Broad scale regional tectonics of Northern area of Pakistan. The Hattian Landslide is marked with a red circle with catchment area of streams. The epicenter of the 8-10-2005 earthquake is marked; the main cluster of aftershocks is located north west of it. The landslide dam is located near the SE-end of the Tanda Fault.

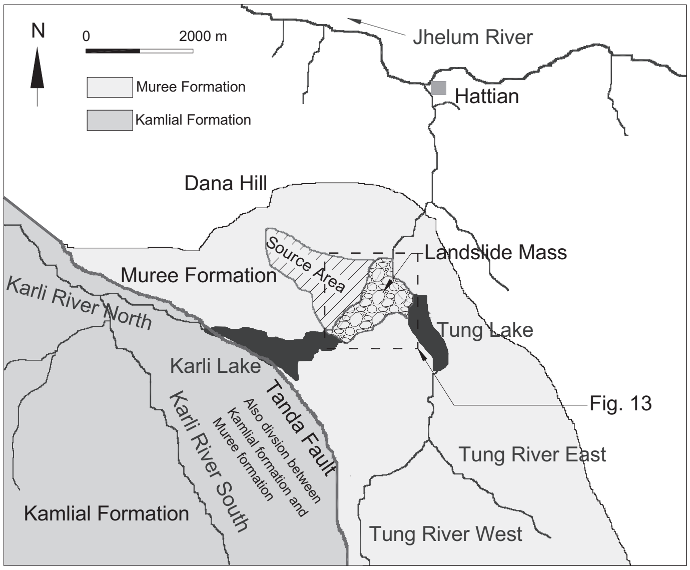


Fig. 2. Schematic map of Hattian Ballah landslide area showing the Tanda fault at south and landslide source scar parallel to the fault. Tanda fault lays the boundary between Kamlial formation and Muree formation. (Compiled from different sources).

Waters from Hattian-ballah joins Jhelum River and Jhelum River initially flows north-west along the Tanda fault before an abrupt turn southward to flow along Murree fault after its junction with already southwardly flowing Neelum River. The location of debris mass is a region of landslide activities which predates the 2005 earthquake.

HATTIAN-BALLAH ROCK AVALANCHE AND LANDSLIDE DAM

Source failure and Formation process

At 3.5 km south of Hattain village a huge landslide mass of volume 85x 10^6 million m^3 was triggered during the earthquake. The collapse of source Dana hill happened in three distinct phases (Dunning, 2007) during its failure parallel to the Tanda fault at south as shown in Fig.2. Initially the landslide mass travelled a maximum drop height of 800m from Dana hill. Then the debris mass raised on the opposite side of the valley while travelling towards the valley. Finally the debris material spread in both northeast and south west direction. After mass impact on the opposite side of the valley, a super elevation is created with a minor valley between the debris mass and opposite side of valley. The resulting debris deposit with length-to-width ratio of 2.5, created a natural dam blocking the waterways of Karli and Tang tributaries of Jhelum River.

A summary of information about the Hattian-Ballah landslide dam and lakes from the assessed and inferred data from various authors is given in (Table 1). Hattian Ballah lies among the huge landslide dams of the world as shown in Fig. 3. Using the data of (Table 1) various geomorphic indicators for Hattain Ballah landslide mass are shown in (Table 2) based on available data of landslide-dammed lakes from Northern Apennine (Casagli and Ermini, 1999), New Zealand (Korup 2004) and selected worldwide (Ermini and Casagli, 2002). The landslide mass is indicated as stable for most of the indicators, apart from few showing it to be unstable.

Characteristics of final deposit and changes

Tanda fault separates the Murree formation from Kamlial formation as shown in Fig 2. It is the red sandstone, siltstone and clay stone formation called Murree formation where the landslide originated. Deposited debris mass is composed of coarser bouldery surface which is relatively shallower part of dam body; a term called Carapace facies (Dunning, 2006). The transportation process produced highly fragmented and angular particles over the surface. Boulder sized Mudstones are expected to be disintegrated at interior of land mass because of their weak and weather able structure.

Flood / Debris Flow Hazard

The huge landslide mass is a possible flood and debris flow hazard for the downstream areas including Muzaffarabad city. As shown in Fig. 1 Jhelum river takes a sharp turn southwards at Muzaffarabad city

Table 1:- Summary of information about the Hattian-Ballah landslide dam and lakes.*

	Characteristics of landslide dam and lake	*Data (assessed and inferred)*
1.	Location and date of dam formation	Hattian-Ballah, 8 Oct 2005 (34°08'N, 73°43"E)
2.	Trigger or cause of landslide	8th Oct. 2005 M=7.6, 44 km from epicenter
3.	Type and characteristics of landslide forming dam	Rock and debris avalanche
	a) Landslide volume	85 million m^3
	b) Landslide scar altitude	2038-1290 m
	c) Length of debris runout (max.)	2609 m
	d) Debris above valley bottom	130 m
	e) Landslide surface area	1.33 km^2
	f) Source maximum length up to deposited surface	1720 m
	g) Source maximum width	520 m
	h) Source average depth	60m
	i) Morphology (Costa and Schuster, 1988)	Type III
4.	Rock type	Miocene Murree formation Mudstones
5.	Underlying causes of landslide	Seismically Reactivated landslide
6.	Landslide dam	
	a) Height of landslide dam	130 m
	b) Width of landslide dam	1587m
	c) Base length of landslide dam	618m
	d) Volume of landslide dam	85 million m^3
	e) Slope of dam faces	Downstream 20-30° / Flat near crest
	f) Status	Overflowing through spillway as on November 2008. Stable with seepage
7.	Physical characteristics of material forming landslide dam	Boulders up to 8m covering the surface at middle part (Murree formation and Mudstones). Surface boulder layer is relatively shallow.
8.	Karli Lake (Large lake)	
	a) Volume	62 million m^3
	b) Catchment area	44.17 km^2
	c) Maximum altitude	2497 m
	d) Minimum altitude	1237 m
	e) Relief	1260 m
	f) Relief ratio	53.7
	g) Mean slope	20°
9.	Tang Lake (Small lake)	
	a) Volume	3.6 million m^3
	b) Catchment area	30.10 km^2
	c) Maximum altitude	2884 m
	d) Minimum altitude	1149 m
	e) Relief	1735 m
	f) Relief ratio	120.7
	g) Mean slope	25°

* Greater part of Data from Dunning 2007 and Schneider, 2008

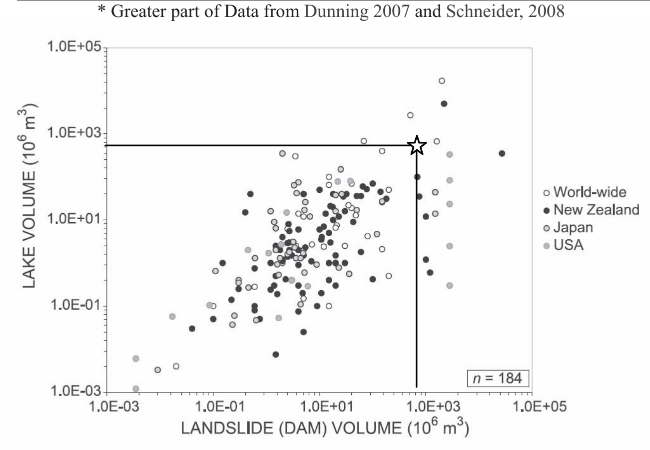


Fig. 3 Bivariate plot of landslide-dammed lake volumes versus landslide dam volume derived from a worldwide data set (n = 184), highlighting occurrences in New Zealand, Japan, and the USA according to Korup (2004) and data from Hattian-Ballah landslide dam and lakes.

while joining the Neelum River. Breach analysis results published in WAPDA, 2006 report indicates a flood wave approaching 30 m for an extreme scenario of 30 minutes breach time along with 1000 year return period storm. Village of Hattain located at the junction of southern branch of Jhelum from landslide mass and west ward flowing Jhelum River. Dammed lakes and debris mass therefore pose flood hazard for downstream areas.

Table 2 :- Geomorphometric indices distinction of discrete domains of landslide dam stability results based on available data of landslide-dammed lakes from Northern Apennine (Casagli and Ermini, 1999), New Zealand (Korup 2004) and selected worldwide (Ermini and Casagli, 2002) and indices values for the Hattian-Ballah landslide dam and landslide-dammed lakes.

Index	*Landslide dam stability*	*Index values for Hattian-ballah*
Blockage Index for Northern Apennine landslide-dammed lakes data, Casagli and Ermini (1999)	$I_b = 3$ threshold ratio for formation of lakes $4 > I_b > 3$ unstable dams $5 > I_b > 4$ uncertainties $I_b = \log(V_D A_C^{-1})$	$I_b = 6.28$ Stable
Impoundment Index for Northern Apennine landslide-dammed lakes data, Casagli and Ermini (1999)	$I_i = 0$ threshold ratio for stable / unstable $I_i = \log(V_D V_L^{-1})$	$I_i = 0.137$ Stable
Blockage Index for New Zealand landslide dammed lakes data, Korup (2004)	$I_b > 2$ threshold ratio for formation of lakes $I_b < 4$ threshold ratio for unstable lakes $I_b > 7$ threshold ratio for stable existing lakes $I_b = \log(V_D A_C^{-1})$	$I_b = 6.06$ Stable
Dimensionless Blockage Index for Selected world wide data, Casagli and Ermini (2002)	$I_b' = 2.92$ is lower threshold ratio for stable, $I_b' = 3.25$ is upper threshold ratio for unstable, $I_b' = \log(H_D A_C V_D^{-1})$	$I_b' = 1.85$ Stable
Dimensionless Blockage Index for New Zealand landslide dammed lakes data, Korup (2004)	$I_b' = 3$ is lower threshold ratio for stable, $I_b' = 5$ is upper threshold ratio for unstable, $I_b' = \log(H_D A_C V_D^{-1})$	$I_b' = 1.85$ Stable
Impoundment Index for Northern Apennine landslide-dammed lakes data, Korup (2004)	$I_i = 1$ threshold ratio for stable / unstable $I_i = \log(V_D V_L^{-1})$	$I_i = 0.137$ Unstable
Backstow Index for New Zealand landslide dammed lakes data, Korup (2004)	$I_S < -3$ upper threshold ratio for unstable $I_S > 0$ lower threshold ratio for stable Data between these threshold remain inconclusive $I_S = \log(H_D^3 V_L^{-1})$	$I_S = -1.45$ Inconclusive
Basin index for New Zealand landslide dammed lakes data, Korup (2004)	$I_a > 3$ threshold for stable $I_a = \log(H_D^2 A_C^{-1})$	$I_a = 2.35$ Unstable
Relief Index for New Zealand landslide dammed lakes data, Korup (2004)	$I_a > -1$ threshold ratio for stable / unstable dam $I_r = \log(H_D H_R^{-1})$	$I_a = -0.98$ Marginally unstable

where V_D is volume of landslide dam and impoundment [in m^3], V_L is volume of landslide dam and impoundment [in m^3], A_C is catchment area upstream of the blockage [in km^2]. H_D maximum crest height of landslide dam [in m], H_R is the relief upstream of the point of blockage [in m].

WAPDA Report

Soon after formation Water and power Development Authority of Pakistan have been monitoring the landslide mass. Fig. 4 shows inflow into the large lake, small lake and seepage through landslide mass along with the water levels in the small and the large lakes. The seepage through landslide dam increased all of a sudden on 11th January 2006. Water level in large lake was 1276m and projecting back (due to unavailability of data) level in small lake is estimated as 1212m. Seepage is either through the portion of landslide mass above 1276m in front of large lake or above 1212m in front of small lake. Seepage increased and on 23rd January it was again close to discharge into small or large lake. After 30th April the seepage came very close to discharge into small lake. Water level in small lake is decreasing on 30th April. This decrease in water level in small lake started gradually after 21st April. After 21st April till 5th June the seepage, discharge into large lake and small lake are all constant, but the water level of small lake is gradually reducing. So the stored water from small lake is also seeping. It is concluded that piping or seepage channels are formed after 21st April. This seepage initiation time of 21st April 2006 can also be confirmed from the sediment outflow curve (Fig. 5) which shows a final peak on 21st April.

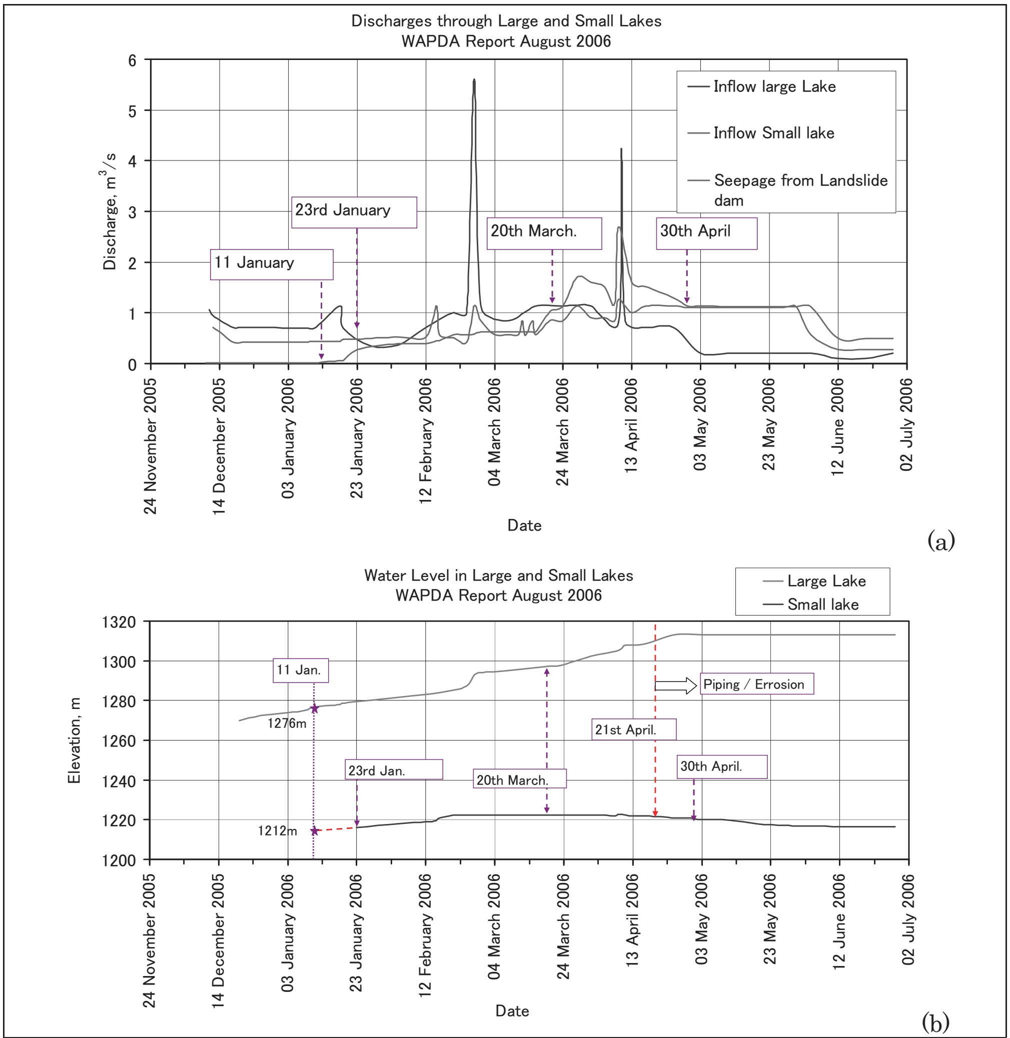


Fig. 4 (a) Discharge into the Large lake, Small Lake and discharge through the landslide mass. Indicating critical changes in the discharges with time. (b) Water level in large and Small lake with time.

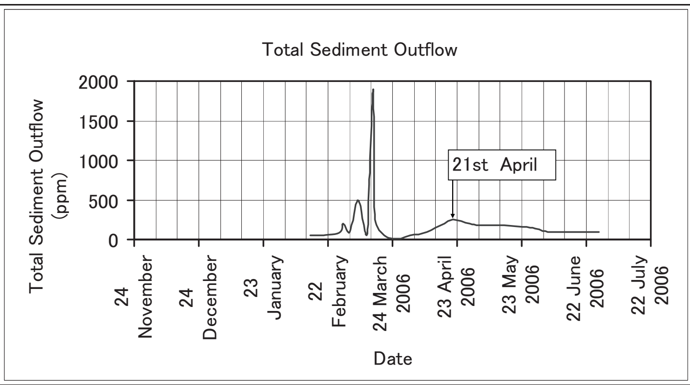


Fig. 5
Total Sediment outflow curve indicating a low final peak on 21st April.

Slaking and Washout process

Rocks from Murree formation are going through the slaking process over the landmass body. The clayey and silty reddish material is crumbled apart due to moisture contact (Fig. 6a). Resulting soil is relatively impermeable and in fact consolidating the land mass. Boulders of Murree formation are disintegrated to form soil dunes around the middle portion of mass body (Fig. 6b).

Apart from the consolidation process occurring on the landmass due to the slaking of mudstones and shale, portion of the slaked material is being washed by the overflowing water from spillway and along water path during monsoon season (Fig. 6c).

Fig. 6a

Fig. 6b

Fig. 6c

Fig. 6(a) Shale of Murree formation crumbled apart due to slaking process. The resulting material is relatively impermeable which is also filling the pours between bigger boulders on the surface. (b) Boulders of Murree formation weathered to form soil dunes around the middle portion of landslide mass. (c) Washout process of weathered material. Dried up path of water during monsoon season show clear reddish sediments deposited on grey sand stones.

GPS OBSERVATIONS

Literature regarding landslide dams is mostly of qualitative nature. Our research team initiated a quantitative approach of GPS measurements for Hattian-ballah landslide mass. The GPS instrument used is Leica GPS1200. Authors conducted GPS survey of the landslide mass twice, once in June 2008 and once in November 2008.

GPS Survey Lines

Two GPS traverse lines were laid. One line along the spillway because maximum settlement was expected along spillway (Longitudinal Line) and one line across longitudinal line (Transverse line). GPS points along with UTM coordinate for June 2008 survey are shown in Fig. 9. In November 2008 survey few points very missed due to unavailability of satellite signals at those points. Total of five points were lost, four along longitudinal line and one along transverse traverse line.

Accuracy of GPS Measurements

Geometric dilution of precision (GDOP) for both surveys was generally observed to be below 5, which is generally accepted threshold for precise measurements. Therefore the accuracy of measurements for both surveys was good. GDOP for GPS points along longitudinal and transverse GPS points are given in Fig. 10. Tripod was used for better accuracy in November 2008 survey.

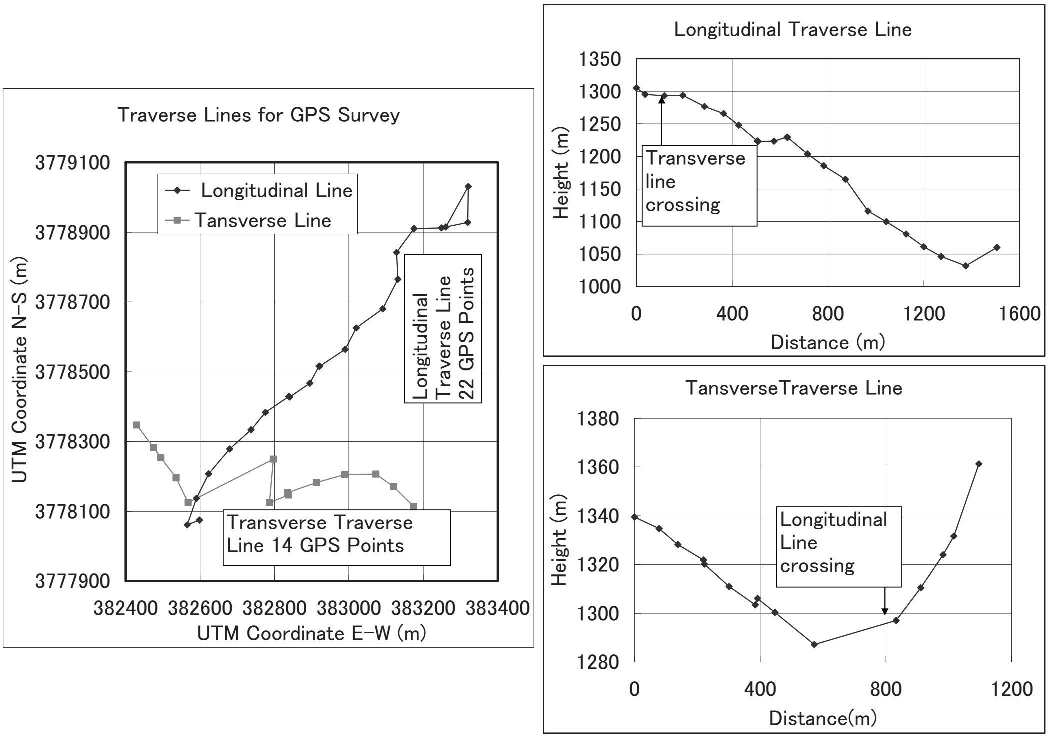


Fig. 9 UTM Coordinates of GPS points. Elevations for Longitudinal and Transverse Traverse lines. (June 2008 Survey Data)

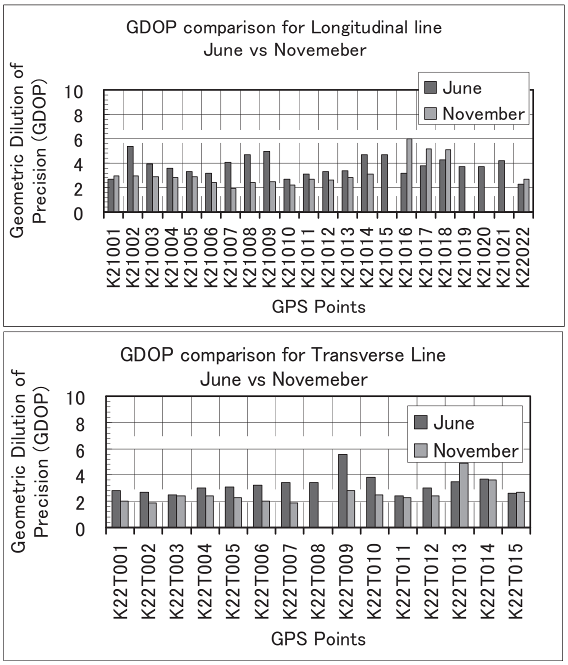


Fig. 10 Geometric dilution of precision for June 2008 and November 2008 surveys. Average of 3.7 and 3.1 for June and November survey respectively for longitudinal lines. Average of 3.0 and 2.5 for June and November survey respectively for transverse traverse line.

GPS Survey results

Results of comparison of GPS data for June 2008 and November 2008 surveys are presented in Fig. 11. Result shows an average settlement of 1.34 m for the longitudinal line with average of 1.72 m for the middle portion of landmass. The transverse line shows an average settlement of 1.46 m. Longitudinal line showed a northwestward movement for region from crest up to half of its length. Transverse line showed a similar trend of westward movement for its eastern half length and no clear trend for the western five GPS points lying on source area of landslide. Generally the GPS data shows a northwestward trend of landmass movement.

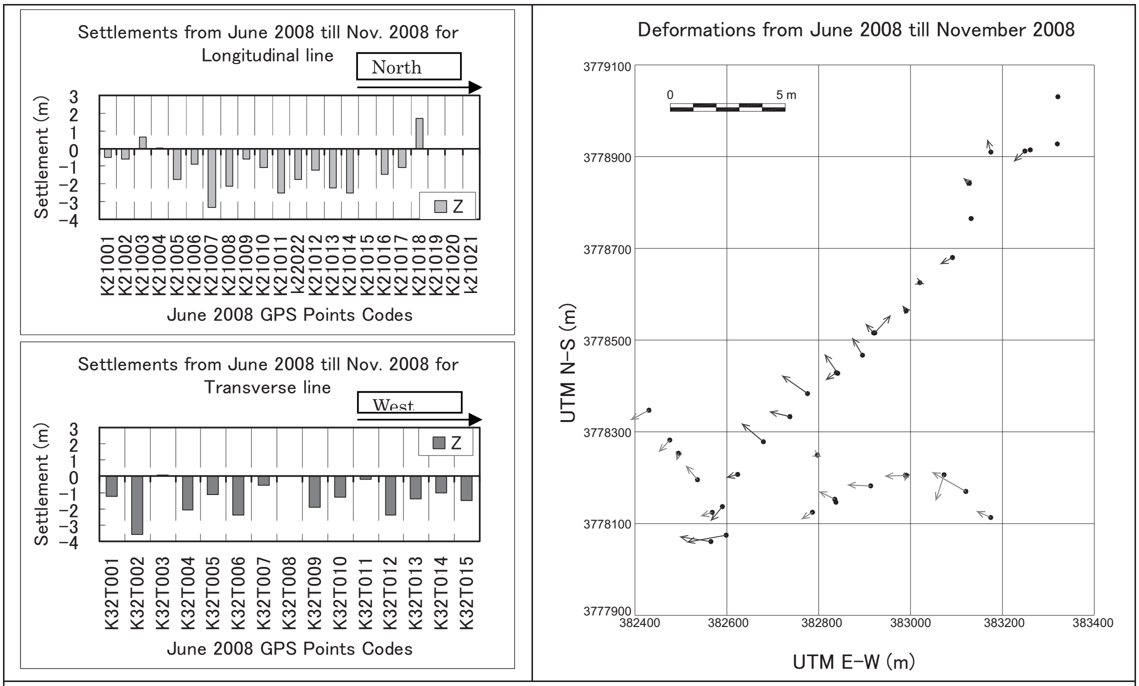


Fig. 11 Results of GPS Data comparison of June 2008 and November 2008. Settlements for Longitudinal and Transverse lines shown on left. Deformation vectors in N-S and E-W UTM coordinate plan shown for each GPS point shown on right.

ISOTOPES STUDY

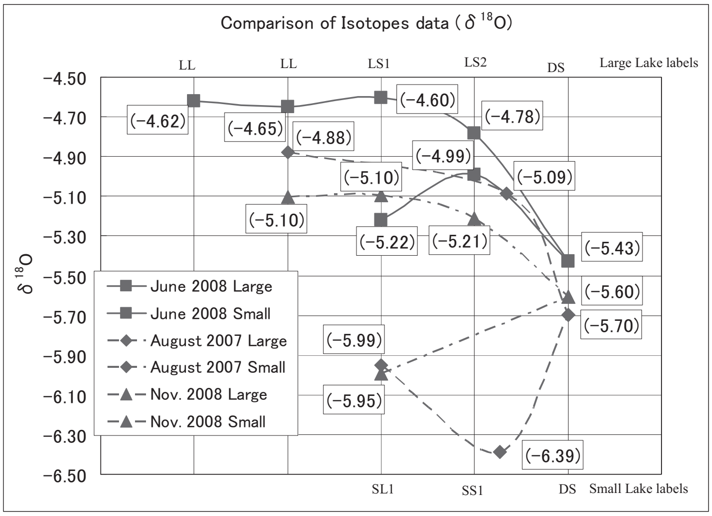
Water samples from the water in lakes, spillways and downstream were taken during the surveys in order to determine the $\delta^{18}O$ ratios. The $\delta^{18}O$ ratio shows the percentage of stable isotopes of ^{18}O relative to ^{16}O isotopes of water. Measurements are made relative to internationally accepted standard VSMOW[1].

$$\delta = \frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}} x1000$$

A positive ‘δ’ value indicates that sample is “enriched” and a negative sample is “depleted” relative to the VSMOW[1]. Under specific conditions, there is a separation of heavier and lighter isotopes, the process called “fractionation”. When water evaporates the lighter isotopes of water (^{16}O) evaporates first while heavy isotopes (^{18}O) remain, due to stronger molecular bond. As the theory of isotope enrichment accompanying the evaporation process is now fairly well advanced, there have been attempts to quantify the water balance of lakes, based on degree of enrichment of stable isotopic

[1] VSMOW “Vienna Standard Mean Ocean Water”

species in them (IAEA, 1981).
Fig. 12 shows the determined $\delta^{18}O$ ratios for water samples from August 2007, June 2008 and November 2008 surveys. It was inferred from $\delta^{18}O$ ratios of water samples from August 2007 and June 2008 that water from deeper layers may be joining the downstream because of the fact that downstream isotopes values were greatly depleted then values of lakes or there spillway. $\delta^{18}O$ ratios of small lake for November 2008 water samples are again closer to value determined in August 2007. Therefore the scenario thought may not be correct because the small lake water is going through large seasonal changes in its isotopic composition as compare to gradual changes for large lake with season. The seasonal fluctuations in isotopic composition are largest in small lakes with short residence time and are dampened in larger systems (IAEA, 1981). On the other hand inhomogeneity occur in the vertical dimension as a result of seasonal stratification (meromixis), thus isolating the deeper water masses (hypolimnion) from surface waters. This stratification in the large lake is thought to be present within the shallower parts of both lakes. Therefore it is inferred that the water from the lakes is still seeping only from the surface courser part of landslide mass. Apparent variation in small lake isotopes values can also be due to the seepage of water from large lake to the small lake as the $\delta^{18}O$ ratios at the large lake is higher and can be an easier source of isotopes variation because of elevation difference of two lakes.



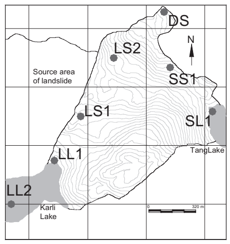
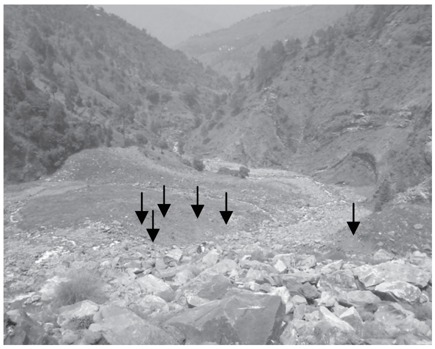


Fig. 12 $\delta^{18}O$ ratios for water samples from August 2007, June 2008 and November 2008 surveys.

November 2006



June 2008

Fig. 13 Toe part of landslide dam. Gradual erosion at parts indicated by arrows.

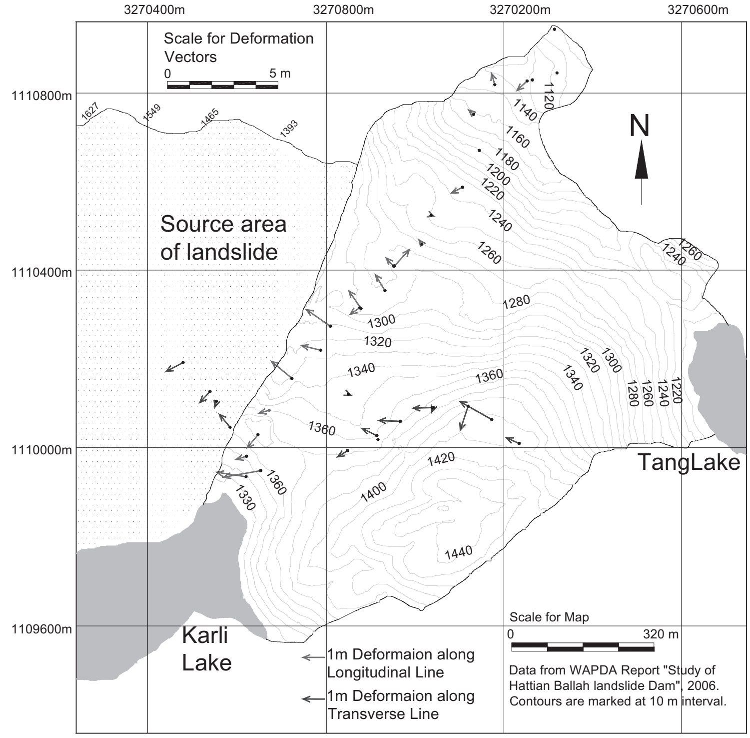


Fig. 14 Deformation Vectors superimposed on contour map. Map reproduced from WAPDA Report "Study of Hattian-Ballah landslide dam, 2006". Northwestward trend of GPS points for southern half length of longitudinal line and Eastern half length of transverse line.

DISCUSSION

Natural landslide dams usually break within few years or otherwise consolidate with time. The water level from Large Lake reached the excavated spillway level at the end of March 2007 and overflowed from spillway then after (Dunning, 2007). According to NESPAK the spillway is performing well and the lakes are now handed over to Government of Azad Jammu and Kashmir. The authorities are now less concerned of the possibility of failure of landslide dam. However since the formation of landslide dam, there has been no major landslide into the Karli Lake (which is of major concern).

GPS Data showed a northwestward movement trend of the landslide mass (Fig. 14). During the formation process super elevation was created on the opposite side of valley and at the toe of landslide source area a gorge was created through which the spillway was latter excavated. GPS data indicates that the landslide mass is moving towards the lower portion. The settlement results are surprisingly large with average settlement of 1.34m and 1.46m for longitudinal and transverse GPS points respectively.

Deformations vectors and settlements of GPS points are composed of three main factors. Mass movement of dam body, the slaking process and subsequent washing and consolidation processes are components of resulting deformations. Last two factors are prominent near the toe part where the mass movement is less prominent because of lesser thickness of debris mass. Fig. 13 shows changes in the toe part from November 2006 till June 2008.

$\delta^{18}O$ ratios indicates the seepage from top coarser layer of debris mass. More water samples are required, especially at different depths of lakes along with some samples of rain water, in order to determine the depth variation and inflow values respectively of the lakes. The likely scenario of seepage of water from Large Lake to Small Lake has to be checked (using a 3 dimensional seepage model under processing). Using all information of isotopes values the depth of seepage zone through the landmass can be assessed.

Concentrating on the debris mass alone will rather be an unsafe approach for stability analysis. On the left bank of Karli Lake there are a number of active slides hanging in equilibrium. These masses at stage of their critical stability can fall into the large lake and eventually they can cause overtopping and therefore breaching of dam body.

The mitigation measures done so far are valuable (excavation of spillway and preparation of hazard zonation map); however there is still certain amount of remaining risk, particularly towards the banks of large lake. Landslide mass seems to be stable for now, but there is a need of further detailed investigation and monitoring of land mass itself and active landslides on the banks of lakes. Knowing the hazards, risk awareness and preparedness on all levels can help save lives and property loss. This study is a part of ongoing research investigating the long term post earthquake issues of Kashmir and mitigating the problems the people are facing after 2005 Kashmir earthquake, which could eventually help ascertain the future evolution of landform of Kashmir.

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