Application of case history based investigations for the stability study of a recent landslide dam

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ABSTRACT
Landslide dams are complex geomorphologic features which usually exist temporarily at the interface between hill-slope and the valley-floor. These temporary natural features have a potential of downstream damage resulting from possible failure. Brief accounts of two such landslide dams are presented along with a summary of the investigations conducted to study their failure potentials: *South Fork Castle creek landslide dam* near Mount St. Helens, Washington, USA and *Hattian Bala landslide dam* near Muzaffarabad, Kashmir. Although, these natural features formed in different parts of the world with different geologic settings, the case history of the earlier served as basis for formulating the investigation methodology for the stability study of the later. The comprehensive site investigations include topographic profiling, sampling of the matrix material for laboratory investigations (index properties, geomaterials classification, permeability and internal erosion potential assessments, electrical resistivity tests), slug tests and monitoring of water levels in the piezometers, time-lapse-water-infiltration field electrical resistivity surveys, seepage and deformation analyses via computer simulations and hydrological database seepage assessments. This paper is an endeavor to briefly document how an earlier case history was applied to conduct the investigations for a recent landslide dam. It will possibly help in improving the understanding of the complexities of landslide dams and derivation of indicators for instantaneous hazard appraisals for future similar events.

RÉSUMÉ
Glissement de terrain barrages sont des caractéristiques géomorphologiques complexes qui habituellement existent temporairement à l'interface entre la colline de la pente et le fond de la vallée. Ces caractéristiques naturelles temporaires ont un potentiel de dommages en aval résultant de défaillance possibles. Brefs comptes de deux tels barrages de glissement de terrain sont présentés avec un résumé des enquêtes menées pour étudier leurs potentiels d'échec: *ruisseau South Fork château barrage* près de Mont Saint Helens, Washington, USA et le *barrage de glissement de terrain Hattian Bala* près de Muzaffarabad, Kashmir. Bien que ces caractéristiques naturelles forment dans différentes parties du monde avec différents paramètres géologiques, l'histoire de cas de la plus ancienne servi de base pour la formulation de la méthodologie de l'enquête pour l'étude de la stabilité de la plus tard. Les enquêtes de site complet comprennent le profilage topographique, échantillonnage de la matière de matrice pour les examens de laboratoire (propriétés index, classification des géomatériaux, perméabilité et évaluations potentiel interne de l'érosion, tests de résistivité électrique), la limace des tests et la surveillance des niveaux d'eau dans les piézomètres, des sondages de résistivité électrique de champ de temps-lapse-eau-infiltration, des analyses d'infiltration et de la déformation via des simulations sur ordinateur et des évaluations d'infiltration de base de données hydrologiques. Ce document est un effort de documenter brièvement comment une histoire de cas antérieure a été appliquée pour mener les enquêtes pour un barrage récente de glissement de terrain. Il aidera peut-être à l'amélioration de la compréhension de la complexité des barrages de glissement de terrain et de dérivation des indicateurs pour les évaluations de risque instantané pour les futurs événements similaires.

1 INTRODUCTION

Landslide dams are common, yet complex and composite geomorphologic features. Their significance lies in temporary existence at the interface between hill-slope and channel or valley-floor system. Stream impoundments by landslide debris accumulation are regarded as events on geomorphologic timescales, owing to their rapid formation and usually limited lifespan. This temporal disruption of water channels by landslide dams can pose a substantial hazard, mainly perceived in mountainous areas. Generally, such dams either break within the first year or stabilize with time (Schneider 2006). Accounts of catastrophic outburst floods from naturally dammed lakes causing downstream damage have been reported from many regions of the world. These accounts demonstrate a wide range of longevity, spanning from a few minutes to hundreds of years (Korup 2002). Although, previous work on landslide dams has resulted in comprehensive documented literature on the subject, the multivariate geomorphic characteristics inherent in landslide dams, however, continue to pose significant problems for defining a basis of comparison.

The devastating 7.6 M earthquake which occurred on October 8, 2005 affected the Northern Pakistan and Azad Kashmir. In addition to the excessive loss of lives and infrastructure damage, it also generated innumerable landslides in the affected hilly areas. The largest landslide was a rock avalanche that occurred near Hattian Bala town, Muzaffarabad, Azad Kashmir. This huge landslide blocked two tributaries of the Jhelum River at their confluence, namely Karli and Tang water channels, resulting into two lakes (see Figure 1). The accounts of this event have been reported previously (e.g. Schneider 2006; Dunning et al. 2007; Niazi et al. 2009, 2010). To assess the possibility of downstream damage due to failure of this natural dam, multiple studies were undertaken and developing scenarios monitored by various national and international agencies. The authors of this paper had an opportunity to conduct an independent study, employing unique sets of investigations.

In order to formulate a methodology, previously reported cases on large landslide dams were reviewed. Of interest is the case study of debris-avalanche dam at South Fork Castle Creek near Mount St. Helens, Washington, reported by Meyer et al. (1994). Apparently, there may be no comparison between the two events in terms of cause of occurrence, composition of geomaterials, geographic location or the pre- and post-event topographic profiles. Schuster & Costa (1986) reported that seepage erosion is more likely to occur in landslide dams because they are more heterogeneous than embankment dams and have not undergone the systematic compaction. Therefore, the common basis of investigating failure potential due to seepage erosion and the initial mitigation measures was considered adequate for the purpose. This paper presents summarized accounts of these two cases and the investigation methodologies employed to study their respective failure potentials, highlighting commonalities and variations.

2 ACCOUNTS OF THE EVENTS

2.1 South Fork Castle Creek Landslide Dam

On May 18, 1980, eruption of Mount St. Helens, Washington, USA resulted in sweeping down the North Fork Toutle River valley of a debris avalanche and creation of a landslide dam in the mouth of South Fork Castle Creek (see Figure 2) which blocked runoff from an area of about 7.8 km^2. The blockage was approximately 600 m long and averaged 425 m in width from the lake to the downstream toe. Maximum heights of the blockage above the maximum lake level and downstream toe were 29 and 58 m, respectively. The height from the lake to the crest averaged 18 m. Thickness of the blockage ranged from 0 to 75 m and was generally greater than 15 m. Slopes from the crest toward the lake averaged 28%. Slopes from the crest toward Castle Creek ranged from 10% to 41%; steepest slopes are in western part of the dam.

The U.S. Geological Survey began monitoring changes in the stages and volume of Castle Lake, which formed behind the dam. The lake filling curve with time is shown in Figure 3. It was anticipated that the lake would overtop the dam by December 1981 or January 1982. The U.S. Army Corps of Engineers constructed a spillway at the eastern end of the blockage in October 1981, stabilizing the lake elevation. Dam failure could still result in flooding along the Toutle River valley. Accordingly, an analysis of the potential for failure of the blockage by seepage erosion was conducted by Meyer et al. (1994) using data from field investigations, summarized later in this paper.

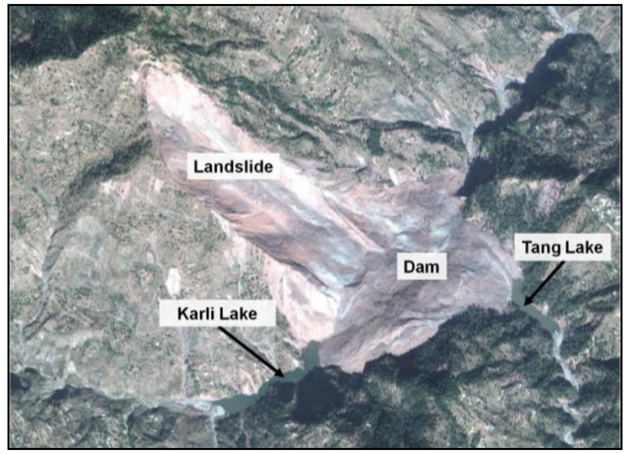

Figure 1. Satellite imagery of Hattian Bala landslide and dam (Denlinger and O'Connell 2006)

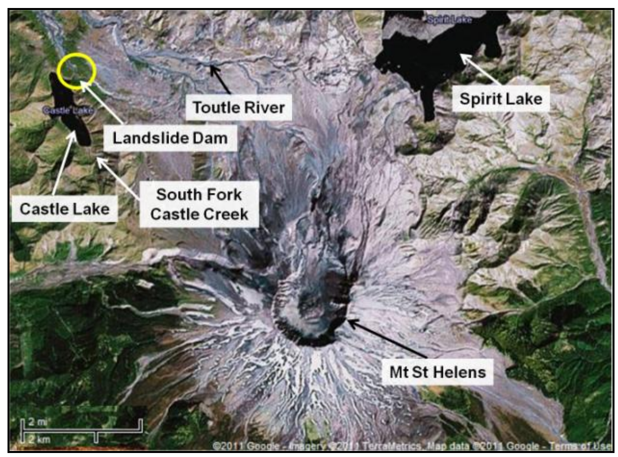

Figure 2. Satellite imagery of South Fork Castle Creek landslide dam (Google Map 2011)

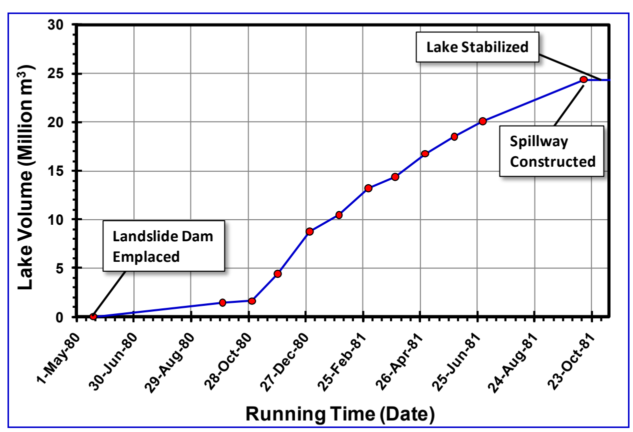

Figure 3. Filling curve of Castle Creek Lake (after Meyer et al. 1994)

2.2 Hattian Bala Landslide Dam

During October 8, 2005 earthquake, the Hattian Bala landslide with debris volume of approximately 85 million m^3 blocked two tributaries of Jhelum River: Karli and Tang water channels, at their confluence, impounding water on the upstream. The landslide blockage is approximately 965 m long with maximum width of 1530 m from Karli Lake to downstream toe. Elevation difference between the highest point on the blockage and upstream toe is 216 m, while that between highest point and downstream toe is 346 m. The highest point on blockage is 91 m above the Karli Lake maximum water surface elevation of 1358 m above mean sea level (amsl). The slopes from the lowest crest elevation towards the upstream toe averages 60% while that of the downstream side is not uniform (range between 15% and 65%). Thickness of the blockage along the lowest crest elevations above the assumed bed level of Karli channel averages at around 110 m with a maximum of about 175 m.

To avert the possibility of downstream damage due to failure of this natural dam, the Pakistan Army Corps of Engineers constructed controlled unlined spillways along the lowest crest elevations for both the channels (now formed into lakes) following approximately the pre-event channel alignments. Potential hazard of Tang Lake significantly reduced owing to washing out of fines from the portion of landslide debris blocking its flow. Accordingly, steady state seepage conditions developed and water surface elevation in Tang Lake got stabilized. Major portion of the debris accumulated in Karli water channel. Continuous upstream inflow resulted in uninterrupted rise in the surface elevation of the Karli Lake until April 2007, when it got filled to its maximum capacity by impounding approximately 50 million m^3 of water. The filling curve of Karli Lake is shown in Figure 4. The inundation associated with Karli water channel continued to pose a potential hazard of causing catastrophic downstream damage in case of failure of the landslide dam due to seepage erosion. Based on the literature review on similar situations, a detailed set of field and laboratory investigations, and stability analyses were conducted as summarized later in this paper.

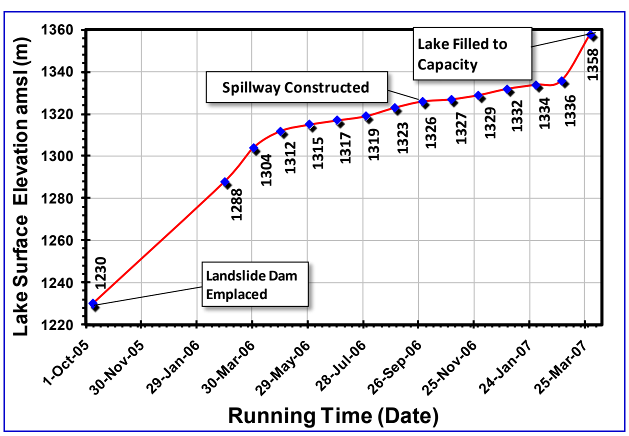

Figure 4. Filling curve of Karli Lake

2.3 Comparison of the accounts from two events

A summary of the key peculiar features relevant to each of the two cases are summarized in Table 1.

Table 1. Summary of peculiar features of South Fork Castle Creek and Hattian Bala landslide dams.

Features	Castle Lake Landslide Dam	Hattian Bala Landslide Dam
Location	South Fork Castle Creek near Mount St. Helens, Gifford Pinchot, WA, USA	3.5 kms upstream of Hattian Bala town, Muzaffarabad, Azad Kashmir
Date of occurrence	May 18, 1980	October 08, 2005
Cause of occurrence	Eruption of Mount St. Helens	7.6 M earthquake
Name of lake created upstream	Castle lake	Karli and Tang lakes
Predominant geomaterial	Dacite, andesite, and basalt; mainly sand and gravel	Sandstone, siltstone, mudstone (shale) and conglomerate; mixture of clay, sand and gravel
Volume of debris material (Million m^3)	Not available	84.5
Max. volume of water in upstream lake (Million m^3)	23.4	50
Initial mitigation measures	Spillway construction	Unlined controlled spillway
Time of spillway construction	Mid-October 1981	End-September 2006
Time of spillway overtopping	Mid-October 1981	End-March 2007
Max. lake elevation (meters amsl)	785	1358

3 INVESTIGATIONS FOR SEEPAGE ANALYSES

Detailed study of the documented case history including the investigations conducted for South Fork Castle Creek landslide dam served as guidelines for the authors to devise investigation methodology for Hattain Bala landslide dam. The specific investigation and analysis tools employed were, however, based on their relevance to the Hattian Bala landslide dam site.

3.1 South Fork Castle Creek Landslide Dam

Meyer et al. (1994) studied the stability of South Fork Castle Creek landslide dam against three modes of seepage erosion: (I) heave; (2) piping; and (3) internal erosion. They estimated the vertical and horizontal hydraulic gradients using digital model (simulating groundwater flow in the blockage). The stability against heave and piping was examined by comparing vertical and horizontal hydraulic gradients, respectively, in the blockage to the calculated critical gradients. Analysis for internal erosion compared material properties of the dam to critical properties for embankment dams that have experienced subsidence or settlement. Following is a list of investigations and analysis activities thus conducted:

- Post landslide topographic profiling of the dam
- Measurement of seepage discharge from the dam on selected dates of dry periods between 1981 and 1984
- Determination of physical properties (e.g., specific gravity, void ratio, and particle size distribution etc.) of the dam materials from seven shallow samples
- Slug tests in piezometers in a nearby debris-avalanche deposit, with properties identical to the study area to estimate lateral hydraulic conductivity
- Observation of water levels in the piezometers installed at seven locations on the dam
- Construction of flow nets
- Simulation of three-dimensional groundwater movement from digital model using finite-difference techniques to approximate solution of the steady- and unsteady-state groundwater flow equations and to predict water levels for calculating horizontal and vertical hydraulic gradients
- Comparison of calculated horizontal hydraulic gradients with the gradients of 200 dams previously failed in piping
- Empirical approach of comparing the grain size distribution with the Sherard grain-size envelope, suggested by Sherard (1979) from the study of failures caused by internal erosion of nine embankment dams
- Application of alternate filter criteria suggested by De Mello (1975) and Sherard (1979) by finding the ratio of D_{15} of particle size distribution of coarse fragment to D_{85} of particle size distribution of fine fragment (at multiple separation sizes between coarse and fine fragments) and comparing these values with acceptable range of 4 – 5

3.2 Hattian Bala Landslide Dam

At Hattian Bala landslide dam, the selection of feasible and reliable, yet viable investigation tools was dictated by limited accessibility to the site and the scale of the landslide dam. Investigations were aimed at determining the subsurface conditions including stratigraphy, saturation levels and seepage conditions affecting the dam stability. A flow chart explaining the investigation methodology adopted for this study is shown in Figure 5. Following is a list of investigations and analysis activities thus conducted:

- Transverse and longitudinal surface topographic profiling along the length and width of Karli spillway (see Figure 6)

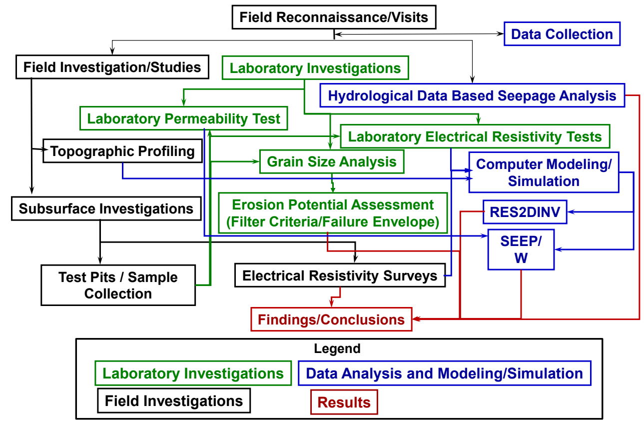

Figure 5. Flow chart of activities: investigations for Hattain Bala landslide dam

- Field sampling of matrix material collected from six locations along the open cut surface of the spillway (see Figure 6)
- Laboratory investigations on matrix materials: index properties, geomaterials classification, permeability assessments, internal erosion potential via Sherard envelope and D_{15}/D_{85} filter criteria, and electrical resistivity tests at different densities and degrees of saturation
- Evaluation of subsurface conditions and time-lapse water infiltration (with time-lapse of three months) via 2-D field electrical resistivity surveys conducted along the length and widths of Karli spillway (see Figure 6)
- Validation of field results of electrical resistivity surveys through laboratory electrical resistivity tests

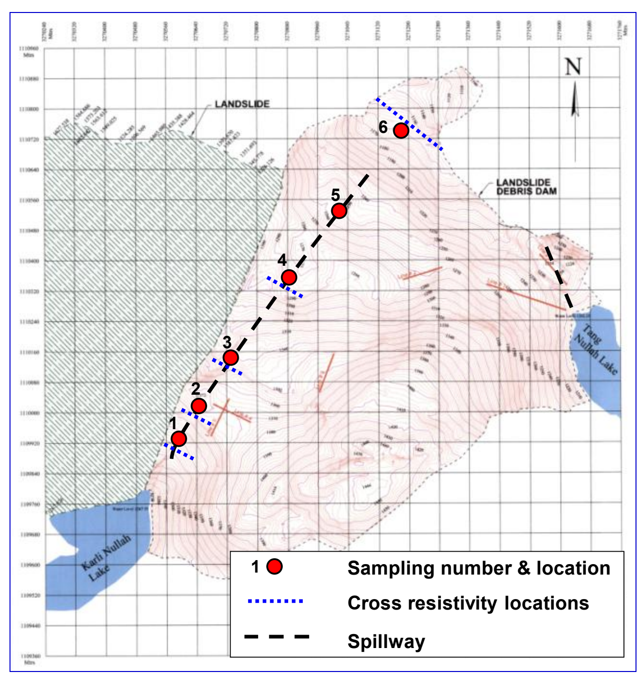

Figure 6. Contour map showing spillway alignment, and sampling and resistivity survey locations

- Seepage analyses via computer simulations on representative model prepared according to the actual topography and laboratory assessed permeability values
- Stability analyses to evaluate the stresses, strains and deformations in the dam body
- Hydrological database analyses to estimate the seepage trends developing through the dam body by comparing the daily upstream inflows from the two lakes with the daily downstream discharge for dry and wet periods together with assessment of the daily precipitation and volume of water accumulating in Karli lake

4 RESULTS AND INTERPRETATIONS

4.1 South Fork Castle Creek Landslide Dam

Based on the investigations, Meyer et al. (1994) derived the following results and the ensuing interpretations concerning South Fork Castle Creek landslide dam:

- The landslide dam material is poorly sorted and contains varying amounts of sand, gravel, silt, and clay. However, 84 – 93% of the sampled material is sand and gravel.
- The lateral hydraulic conductivity of the dam material ranges from 0.7 to 1.5 m/day and averages 0.8 m/day.
- The ratio of horizontal to vertical hydraulic conductivity is approximately 10 to 1 over most of the blockage.
- Ground-water movement and water levels are not considered to be characteristic of embankment dams.
- The elevation of the water levels in the blockage varies with time, indicating seasonal changes in recharge and discharge.
- The average annual discharge rate from the downstream seeps is between 0.02 m^3/s and 0.005 m^3/s.
- Approximately, 81% of the total inflow into the landslide dam was from infiltration of precipitation, and 18% was inflow from the lake. Approximately 81% of discharge from the blockage was through the seeps. The remainder discharged to the lake, Castle Creek, and as underflow beneath the creek.
- The rates of seepage from the dam may vary seasonally, but will remain relatively stable over a period of years, unless soil erosion causes increased seepage.
- Values of the factor of safety against heave (defined as $FS_{heave} = i_c/i_e$, where i_c and i_e are the critical and the exit hydraulic gradients, respectively) range from 5 to 22.7. These values are slightly lower than those recommended in the literature. The blockage was expected to experience local failure by heave because it was composed mainly of fine sand through gravel.
- Calculated horizontal hydraulic gradient values range from 0.04 to 0.1, indicating local piping possibilities. Given the location of flow net relative to the lake, the blockage was considered to be overall stable against failure due to piping.
- Sherard's empirical approach suggests that the blockage is potentially susceptible to internal erosion.
- The mean for the D_{15}/D_{85} values is 4.6, within the acceptable range of 4 to 5. However, for the overall range: 2.5 to 7.1, the dam material was considered marginal in resistance to internal erosion.

On the basis of these results and interpretations, Meyer et al. (1994) suggested constant monitoring of the Castle Lake blockage for indications of seepage erosion, such as surface heaving or subsidence.

4.2 Hattian Bala Landslide Dam

The investigations for Hattian Bala landslide dam were completed in April 2007. Following results and the ensuing interpretations were derived:

- Hattian Bala landslide dam is a heterogeneous body of mass in terms of both material composition and dimensions. The dam body comprises of materials ranging in size from boulders to clay size particles. Table 2 and Figure 7 present the results of the classification analysis conducted on samples of matrix material collected from the Karli spillway.
- The overall permeability of dam material is very low (see Figure 8).
- Pockets of high resistivity (high density) zones exist within certain portions of the blockage. From the different field electrical resistivity surveys conducted as part of investigations, one longitudinal profile along the Karli spillway and one transverse profile across the spillway are shown in Figures 9 and 10, respectively, to show such zones of high resistivity. The laboratory resistivity test results, presented in Figure 11, along with the range of permeability values shown in Figure 8 enable establishment of possible relationship between field resistivity, density, permeability and degree of saturation. Thus, the high density zones in the field resistivity profiles have relatively lesser permeability values than the saturated zones, which in turn hinder the steady flow of seepage water from saturated zones, resulting in an uneven ground water flow pattern.

Table 2. Classification of samples of matrix material from Hattian Bala landslide dam.

Sample No	Particle Size Distribution (%)			LL (%)	PL (%)	PI	USCS
	Gravel	Sand	Silt/Clay				
1	37.7	42.5	19.8	19.8	16.0	3.8	SM (d)
2	26.8	49.5	23.7	24.7	16.3	8.3	SC
3	47.3	30.3	22.4	17.6	13.4	4.2	GM-GC
4	48.3	31.9	19.8	18.8	16.1	2.7	GM (d)
5	42.6	11.8	45.6	19.5	12.6	6.9	GM-GC
6	37.4	25.4	37.2	20.2	13.4	6.8	GM-GC

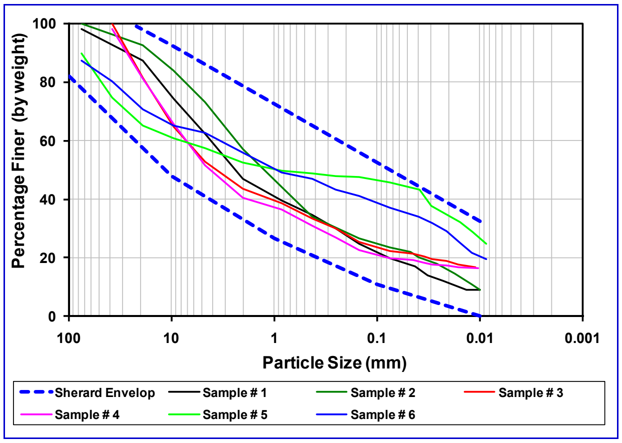

Figure 7. Grain size distribution of the samples of matrix material from Hattian Bala landslide dam

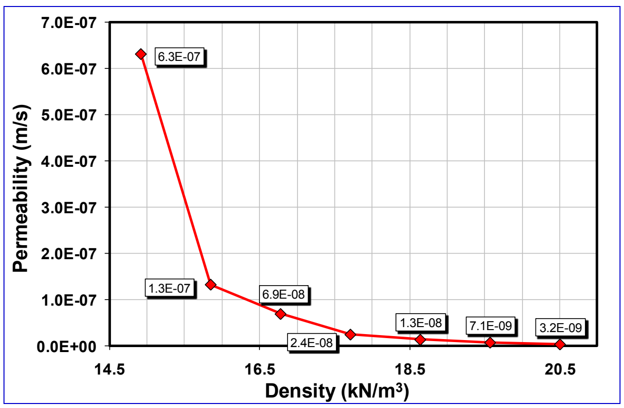

Figure 8. Measured permeability for different densities of the matrix material from Hattian Bala landslide dam

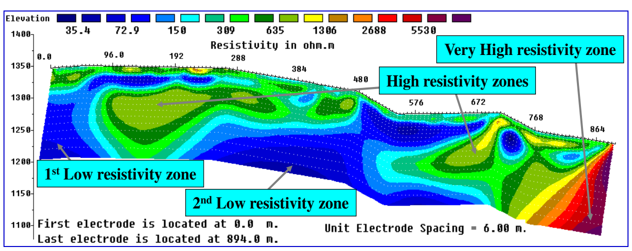

Figure 9. Karli spillway longitudinal subsurface resistivity profile from RES2DINV modeling

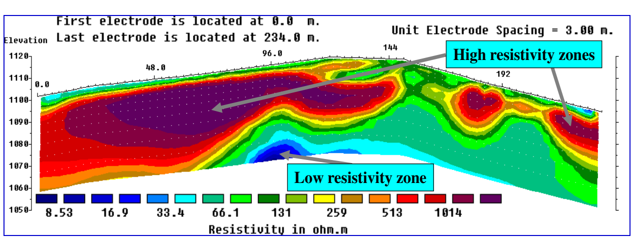

Figure 10. Transverse subsurface resistivity profile at the dam toe from RES2DINV modeling

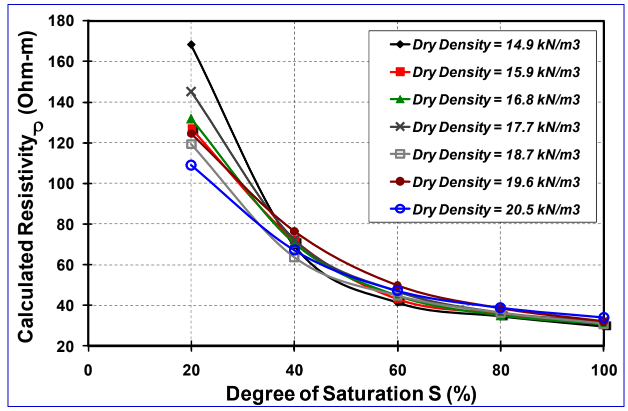

Figure 11. Laboratory resistivity results for different densities and degrees of saturation

- Figure 12 shows the average daily discharges and the daily precipitation, while Figure 13 shows the daily surface elevations of the two lakes for the month of October 2006 (the actual monitoring period spanned from February to December 2006).
- The hydrological data compared to the size of spillway and obstructions to the smooth flow of water due to planned placement of boulders in the bed of spillway indicate infiltration of water into the dam body.
- Since emplacement of the dam, the degree of saturation within the dam body has been increasing constantly (assessed from the time lapse water infiltration electrical resistivity surveys), commensurate with increase in the water level of Karli Lake.
- It is postulated that the increase in saturation level and extents of the saturated zone within the dam body is progressing due to seepage from the upstream toe of the dam and infiltration of precipitation on the surface of dam as well as the surface flow.
- Seepage discharge, which first developed in the month of March 2007, indicated signs of internal erosion in the form of suspended sediment concentrations. This discharge is expected to increase in terms of scale and locations with increase in saturated zones within the dam body. Constant monitoring of the suspended sediment concentration in the seepage discharge can give a fair assessment of the rate of internal erosion.

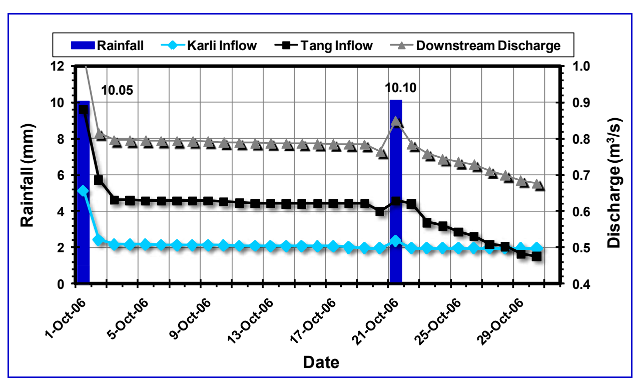

Figure 12. Daily discharges and rainfall: Oct. 2006

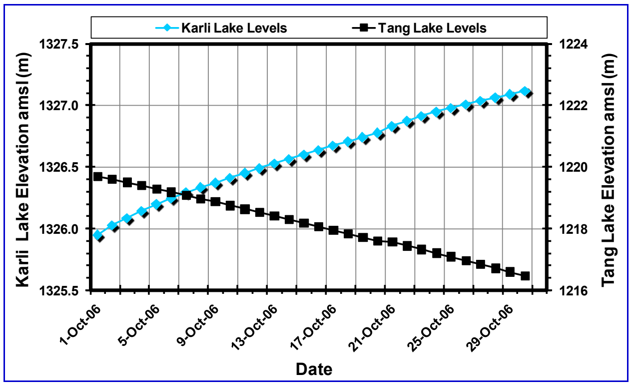

Figure 13. Daily surface elevations of Karli and Tang Lakes: October 2006

- Seepage discharge is also a sign of release of excess pore water pressures developing within the dam body. This phenomenon will help in attaining steady state conditions.
- The hydrological data based analysis failed to determine the part of seepage volume infiltrating into the dam body due to the number of unknown and un-gauged variables.
- Based on the measured permeability values of the matrix material, it can be the judged that Karli Lake water level is not expected to lower significantly in a short span of time. However, extended constant monitoring of suspended sediment concentration in seepage discharge can aid in better assessment of this possibility.
- Matrix material composing the dam body is significantly non-resistant to internal erosion due to seepage as well as erosion due to overtopping flow. It can be seen from Figure 7 that the grain size distributions of all the samples lie within the Sherard envelope. An example of application of alternate filter criteria [no erosion boundary (D_{15}/D_{85})] on the samples collected from the dam is shown in Figure 14 and the summary results are presented in Table 3. Most of the D_{15}/D_{85} ratios lie outside of the acceptable range of 4 – 5, clearly establishing the erosion potential of the overall matrix material forming the dam body.

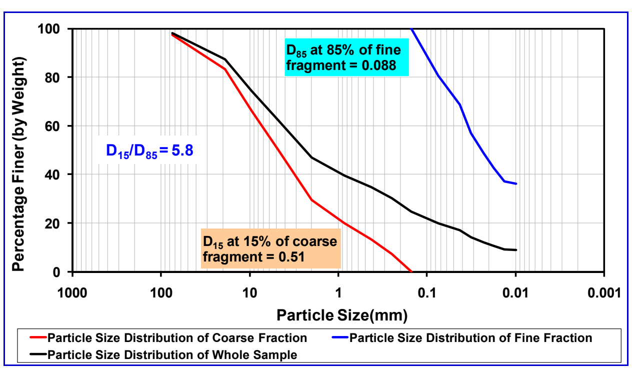

Figure 14. Grain size distribution of sample 1, separated at 0.15 mm

Table 3. D_{15}/D_{85} ratios for samples from Hattian Bala landslide dam separated at selected particle sizes

Sample no.	Particle size of separation (mm)						Mean D_{15}/D_{85} ratios
	0.15	0.43	0.85	2.00	4.75	9.53	
1	5.8	6.1	5.7	3.7	2.5	2.0	4.3
2	10.2	4.0	2.7	2.6	2.5	2.4	4.1
3	9.1	9.5	7.7	6.1	3.4	1.9	6.3
4	14.7	9.5	7.3	6.3	2.8	1.7	7.1
5	103.2	114.3	127.7	135.2	26.9	14.4	87.0
6	21.1	15.5	13.1	9.0	9.8	9.2	13.0
Mean D_{15}/D_{85} Ratios	23.5	22.8	23.6	23.6	7.5	5.9	20.3*

*Overall Mean

- Prediction of the rate and progress of internal erosion is very difficult owing to extreme heterogeneity of the material within the overall dimensions of the dam.
- Relatively, the more dominant erosion mechanism would be due to overtopping flow, initiating headcut near the toe, which is likely to advance upstream until crest of the dam starts eroding. Moreover, since, the dam is not configured with uniform slopes on downstream side, this phenomenon is likely to develop and advance at multiple locations along the spillway.
- Under normal static conditions, any chance of catastrophic failure is a rare possibility. Progressive failure due to erosion of fines (internal erosion as well as scouring at the surface) resulting in creation of voids and subsequent settlements is the most likely scenario to develop over extended period of time.
- Hydrogeological immaturity of the dam is the main factor restricting the assessment of time needed for total washing out of fines and final settlement of the embankment before achieving a steady state condition.
- Possible dynamic conditions which can change the scenario include an earthquake of high intensity, sudden increase in discharge due to an extreme event of excessive precipitation or cloud burst and large-scale landslides from the adjoining ridges into Karli Lake generating a flood wave/tsunami.

5 CONCLUSIONS

Case studies of two landslide dams including accounts of events, investigation methodologies adopted for stability assessments and results/interpretations of investigations are presented. The purpose of presenting an earlier case study (South Fork Castle creek landslide dam) is to highlight the importance of documenting case histories that can serve in guiding the practical application of geotechnical investigation tools. This fact has special relevance in case of landslide dams, because of the lack of thorough understanding on the evolution and dynamics of the geomorphologic processes involved and their ephemeral nature. Based on the review of the Castle Creek case study, the focus of investigations for the stability of Hattian Bala landslide dam was directed towards assessment of potential failure due to seepage erosion.

At Hattian Bala landslide dam, the assessment of erosion potential via Sherard envelope and no erosion boundary (D_{15}/D_{85}) criteria served in classifying the dam material as non-resistance to internal erosion. The elaborate hydrological database analysis from the daily upstream and downstream flows combined with the daily precipitation and lake elevations proved inadequate to clearly establish the seepage volume, primarily due to unknown and un-gauged variables. However, a practical method was evolved which can be applied to the study of similar scenarios. The details of this analysis can be found in Niazi et al. 2009. The field 2-D electrical resistivity surveys and the laboratory calibration of resistivity values along with the laboratory permeability tests on the samples collected from the site were the major investigation tools in establishing the subsurface conditions and the seepage trends in the dam body. These also served in preparing the site model that was later used for alternate seepage and deformation evaluations via computer simulations.

It is considered that extension of field electrical resistivity to 3-D survey combined with laboratory calibrations, a well planned monitoring and analysis of hydrological data and erosion potential assessments via Sherard envelope and D_{15}/D_{85} criteria are very strong tools for stability investigation of a landslide dam. However, engineering judgment must be applied in selecting the most appropriate investigation methods that befit the specific peculiarities of each case.

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