CASE STUDY AND FORENSIC INVESTIGATION OF FAILURE OF DAM ABOVE KEDARNATH

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ABSTRACT

Many earthen dams are built on hill sides. Failure of such walls can lead to catastrophic consequences. The effectiveness of a disaster reduction relies on the perception of the disaster itself and proper analysis of the previous experience. From 14 to 17 June 2013, the Indian state of Uttarakhand and adjoining areas received heavy rainfall, which was about 375% more than the benchmark rainfall during a normal monsoon. This caused the melting of Chorabari Glacier at the height of 3800 metres, and eruption of the Mandakini River which led to heavy floods near Gobindghat, Kedar Dome, Rudraprayag district, Uttarakhand, Himachal Pradesh and Western Nepal. Kedarnath, had been obliterated, 608 villages, covering a population of 700,000, in 23 districts of Uttar Pradesh were affected by the flood. Drought in the past year has shown the real pictures of the basins of many dams in India. There is a dangerous levels of silting up reducing both the reservoir capacity and factor of safety. The present average rain fall caused massive flooding all over India. The main result of the Kedernath disaster was a outpouring of silty sediments from the dams along River Mandakini that swallowed up entire villages. Forensic analysis of a failure can significantly improve chances of future success. The present paper is a forensic analysis of failure of dam wall behind Kedarnath temple with respect to danger of silting up of dams and their potential for failures thus help to prevent future such catastrophes in India

INTRODUCTION

An earth or rock fill dam is a geotechnical structure that forms a “barrier” that obstructs the flow of a river. Moraine dams are a special category of earth-rockfill dam naturally formed when glacial debris blocks the path of glacial melt. As they are easily erodible, they need spillways that are designed to safely pass water to the downstream side of the river. They have to have sufficient freeboard to absorb sudden rise in water level caused by snowmelts cloudbursts and floods. Mountain dams tend to get silted up faster as they have greater debris and silt load.

Construction of dams has been known to exist across the Tigris and Euphrates rivers about 5000 years ago. In Tamil Nadu there is a still serviceable dam 1500 years old. The damming of streams and rivers has been integral to human population growth and technological innovation.

Among other things, dams have reduced flood hazard and allowed humans to settle and farm productive alluvial soils on river flood-plains; they have harnessed the power of moving water for commerce and industry; and they have created reservoirs to augment the supply of water during periods of drought. Recently, the risk of natural disasters has increased in the areas below dams as a result of increasing anthropogenic activities (Dhobal, 2013). This trend is likely to increase in the future as human activities will increase. The natural flow paths of the channels get obstructed due to the construction of man-made structures that results in deviation of the flow from its natural course. These are the first to be affected in floods and they are usually either unplanned or illegal in nature.

Dams are categorized generally as earth or concrete dams, depending on the material used to construct it. This paper, discusses failure of an earth dam. Earth dams have their embankments constructed of soil and rock. Properly constructed and maintained earth dams usually have a unending life span. However, improperly constructed and un-maintained dams usually fail as in the present case. A dam failure is a catastrophic type of failure characterized by the sudden, rapid and uncontrolled release of impounded water accompanied by the trapped silt and debris that erode and accumulate additional debris along the way. Major causes of failure of earth dams worldwide include construction flaws, seepage/ piping, overtopping and siltation.(Tandeswara, 1992; ASDSO, 2010) This study shows that siltation and overtopping caused the disaster at Kedarnath.

Sometimes overtopping of a dam could be caused by a poorly designed spillway that is failing to convey excess water away from the dam. Heavy rains from a single tropical storm can cause overtopping as the spillway fails to convey excess flood water thus resulting in the washing away of the dam. The dam above kedarnath did not have a spillway. Excess water usually used to spill out from the back so the need for spillway was never envisioned. The plausible causes of such failure in Kedarnath has been researched by Dobhal et al of the Wadia Institute of Himalayan Geology. (Dobhal, 2013) Dam failure is normally viewed in the context of the risk that is posed to life and property downstream of dams. This is usually so for large dams constructed directly above large population centres. These are capable of causing catastrophic losses. Dam failure can cause loss of life, property damage, cultural and historic losses, environmental losses as well as causing social impacts (Nyoni, 2013)

Case Study cum Forensic Investigation Procedure

Many Earthen Dams are built as part of infrastructure projects in India. They lie mostly on the hillsides and are a potential cause of future danger unless properly constructed and maintained. Failures of one such dam lead to devastating consequences. A disaster reduction plan is essential and its effectiveness relies on the expectation of the disaster itself, previous experience and state of preparedness.

The present case study aims to present the data available in a new light. From the review of the studies carried out by multiple agencies in the area, it is seen that the reasons given for the disaster are inadequate. As a forensic procedure the data was collected from various sources and assimilated and a conclusion was reached that the disaster occurred due to reduced reservoir capacity due to siltation, improper compaction as it was a natural blockage and increase in height without spillway provisions.

We will first study the data available from the source at closest proximity to the site- the Wadia Institute of Himalayan Geology, Dehradun which operate monitoring stations in that area. We will also study the impact of the siltation on the reservoir. From these studies we will draw reasonable conclusion as to the possible plausible cause of the Earthen Dam Failure.

Study area

The Kedarnath temple town (see Fig. 1) is located in Uttrakhand state of India in the western extremity of the Central Himalaya (30 44 6.7 N; 79 04 1 E) in the Mandakini River valley which has a total catchment area of ~67 km2 (up to Rambara), out of which 23% area is covered by glaciers. The Primary deity of Kedarnath is the 'Lord of Kedar Khand' (Shiva) (Wikepedia, 2016). The catchment area is situated in the glacier modified U-shaped valley; the altitude ranges from 2740 to 6578 m asl (above sea level). Such a variation in the altitude provides diverse landscape.

Mandakini River originates from the Chorabari Glacier (3895 m) near Chorabari Lake and joins Saraswati River which originates from Companion glacier at Kedarnath, passing through Rambara and Gaurikund. The Madhu Ganga and Dudh Ganga are the main tributaries that merge into the Mandakini River at Kedarnath town.

The Chorabari Lake (3960 m asl) also known as Gandhi Sarovar Lake is a snow melt and rain fed lake, located about 2 km upstream of Kedarnath town which is approximately 400 m long, 200 m wide having a depth of 15–20 m. The bursting of this lake led to its complete draining within 5–10 min as reported by the watch and ward staff of the Wadia Institute of Himalayan Geology (WIHG) who were present in WIHG camp at Chorabari Glacier on 16 June and early morning of 17 June 2013(Dobhal 2013).

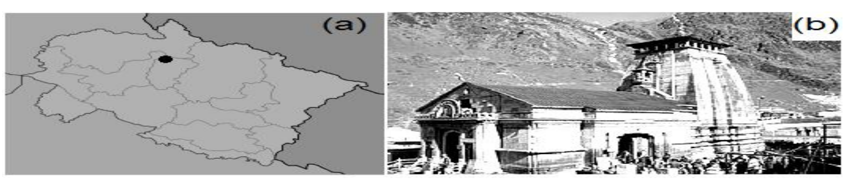

Figure 1(a)Location of Kedarnath in Utrakhand (Wikipedia);(b) Kedarnath Temple

Legend of the Chorabari Lake

The Chorabari lake is a moraine dammed reservoir. It is caused by the natural blockage of a glacial valley by glacial moraine. It causes the resulting sediments to pile up behind the blockage thus creating a reservoir for molten snow, ice and rain. The unstable temple is not directly accessible by road and has to be reached by a 14 kilometers (8.7 mi) uphill trek from Gaurikund. Pony and manchan (porter-carried) service is available to reach the structure. The temple was allegedly built by Pandavas during their journey to heaven and revived by Adi Sankaracharya (the great Hindu reformer) and is one of the twelve Jyotirlingas, the holiest Hindu shrines of Shiva. (Wikepedia, 2016) Kedarnath is an in accessible place even today accessible with great difficulty only six months in a year. With modernization of India’s transport system the rush of pilgrims grew from a trickle in 1900’s to a torrent today. There was an acute shortage of water for consumption. As the area developed, the water from the Snowmelt Rivers was insufficient. The people prayed for divine intervention. It is said that one day as the parched people of Kedarnath prayed to Lord Shiva, and he sent his ‘ling’ down to dam the valley above Kedarnath and created a lake. Over the years the dammed portion was raised and *used for consumption*. When disaster struck it is claimed that that very giant stone (Ling) that had dammed the valley, tumbled down and came and stood between the temple and the mud flow thus protecting the shrine. A huge rock got stuck behind Kedarnath Temple and protected it from the ravages of the flood. The waters gushed on both the sides of the temple destroying everything in their path. Even eyewitness observed that one large rock got carried to the rear side of Kedarnath Temple, thus causing obstruction to the debris, diverting the flow of river and debris to the sides of the temple avoiding damage. (Wikipedia, 2016) It still stands there today a mute spectator to the destruction caused by mans greed and negligence. Deforestation and denudation of vegetation on the slope to feed the firewood-fuel-needs of the ever growing pilgrim population, hap-hazard development, unsustainable augmentation of reservoir height without provision of proper spillway and design freeboard, (see Fig. 2) and no effort to de-silt the reservoir caused and compounded this disaster.

Plausible Causes of Failure

The standard cause of failure was the cloud burst followed by snowmelt and overtopping. The real reason for over topping was the silted up reservoir. We will discuss both the scenarios here.

Recent climate changes have had significant impact on high-mountain glacial environment. Rapid melting of snow/ice and heavy rainfall has resulted in the formation and expansion of moraine dammed lakes, creating a potential danger from dammed lake outburst floods. The Indian Summer Monsoon is the major source of precipitation (rainfall) in the study area with partial contribution from western disturbances during winter. On 16 and 17 June 2013, heavy rains together with moraine dammed lake (Chorabari Lake) burst caused flooding of Saraswati and Mandakini Rivers in Rudraprayag district of Uttarakhand.

Figure 2 the photo shows the raised part of the dam, the breech at the abutment and the silt accumulated in the dam (WIHG).

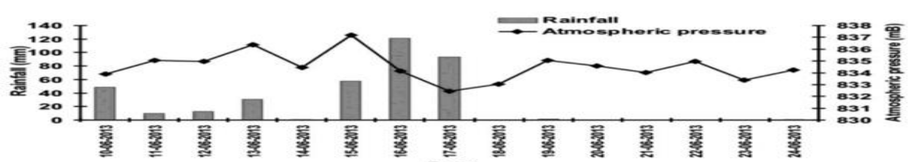

Figure 3 Rain fall and pressure at Ghuttu observatory 38 km from Kedarnath

Prolonged heavy down pour (Figure 3) on 16 and 17 June 2013 resembled ‘cloud burst’ (except for amount of precipitation of 100 mm/h) type event in the Kedarnath valley and surrounding areas that damaged the banks of River Mandakini for 18 km between Kedarnath and Sonprayag, and completely washed away Gaurikund (1990 m asl), Rambara (2740 m asl) and Kedarnath (3546 m asl) towns. The preliminary results suggest that the following two events caused devastation in the Kedarnath area of the Mandakini River basin.(Dobhal et al 2013). This was widely accepted as the official version as it exonerated all responsibility from any one especially the powers that be. Subsequent Analysis of the disaster was only limited to the overtopping and breech. The actual cause of the rapid overtopping was never discussed. This paper suggests that the silting up of the reservoir by glacial deposits combined with the silt pressure to enhance the impact of the disaster.

Preliminary Devastation Event

On 16 June 2013, at 5:15 p.m., the unprecedented heavy rains fell on the Saraswati River and Dudh Ganga catchment area. This resulted in excessive flooding as the flow across all the channels increased beyond safety limits. The slopes were denuded of vegetation due to active deforestation in that area.

Figure 4: (a) Denuded Slope (Dobhal; May 2012 (b)Devastation of the valley See small house in middle left edge for comparison of size. (Gupta 2013)

There was very active erosion creating deep gulleys and causing excessive water and sediment accumulation in the rivers leading from that area (Fig 4). Subsequently, large volumes of water struck the towns down river which as a result of erosion simultaneously picked huge amount of loose sediment en route. The voluminous muddy water studded with debris from the surrounding regions and glacial moraines moved towards Kedarnath town, washing off all newly constructed structures that lay on and blocked the direct path of the flow - Sankaracharya samadhi, Jalnigam guest house, Bharat Seva Sangh Ashram, etc. the whole upper part of Kedarnath was buried and torn apart and leading to the biggest ever devastation ever witnessed in the region. The WIHG meteorological stations near Chorabari glacier recorded 325 mm rainfall at the base of the glaciers in two days on 15 and 16 June 2013. Due to heavy downpour, the town of Rambara was completely washed away on 16 June evening.

Secondary Devastation Event

The second event occurred on 17 June 2013 at 6:45 a.m., after overflow and collapse of the moraine dammed Chorabari Lake which released large volume of water that caused another flash flood in the Kedarnath town leading to heavy devastation downstream (Gaurikund, Sonprayag, Phata, etc.). Our study shows that the main cause of the Chorabari Lake collapse was torrential rains that the area received between 15 and 17 June 2013.

After the heavy rainfall the right lateral basin of the glacier, which is thickly covered by snow more than 2 meters thick near the upper part of lake during June 2013, rapidly melted due to rainwater allowing large amount of water accumulation in the Gandhi Sarovar lake. There were no outlets in the lake, the water was simply released through narrow passages at the bottom of the lake which were already partly blocked by silt. The sudden water accumulation blocked these passages too. Suddenly millions of gallons of water accumulated in the moraine dammed lake within 3 days, which increased their potential energy and reduced the shear strength of the dam. Ultimately the loose-moraine dam breached causing an enormous devastation in the Kedarnath valley (Figures 5 a,b,c,d & 6)

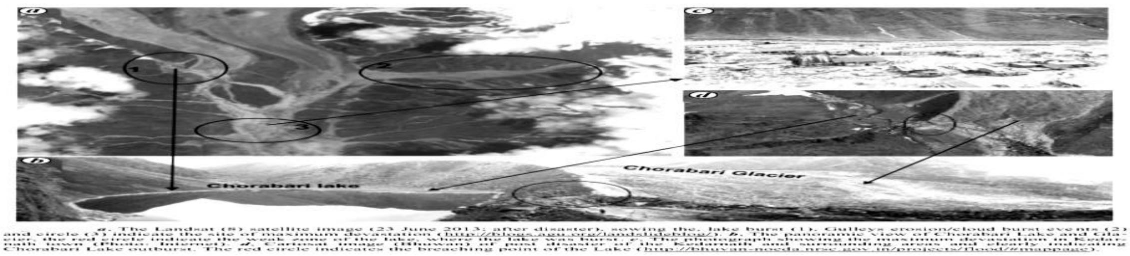

Figure 5: Shows the Devastation at Kedarnath

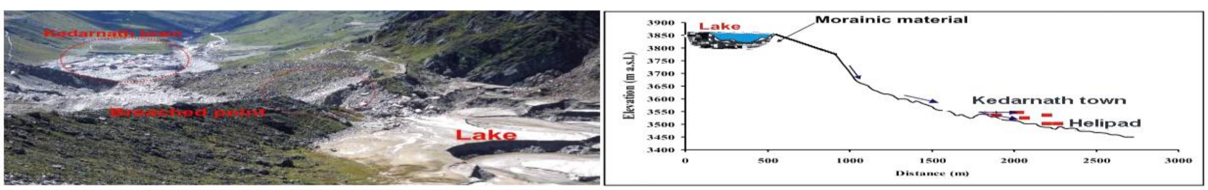

Figure 6: Showing devastation due to silt (Gupta ,2013)

Alternative methods available to prevent dam failure

Many retaining walls are built as part of housing projects on hill sides. Failure of such walls can lead to catastrophic consequences. The effectiveness of a disaster reduction relies on the perception of the disaster itself and previous experience

Analysis by other agencies

Various experts from all over the world studied this disaster; ASI, TERI, IITM, WIHR and many others international and national agencies. There was just too much devastation and too much data floating around. Each analyzed the failure in their own unique way and reached the same conclusion. The danger was caused by excessive runoff, no runoff control (adequate dan storage) and runoff diversion mechanisms and overtopping of the reservoir. But none dared to dwell into why the reservoir overtop. The real reason was simple reduction of capacity due to siltation.

The experts, who were asked by the Archaeological Survey of India (ASI) to examine the condition of the foundation in wake of the floods have arrived at the conclusion that there was no danger to the temple. The IIT Madras experts visited the temple thrice for the purpose. Non-destructive testing instruments that do not disturb the structure of the temple were used by the IIT-team for assessing the health of the structure, foundation and walls. They have submitted their interim report that the temple is stable and there was no major danger (Wikipedia, 2016).

Geologic Study

Geologically, the area north of the Pindari Thrust comprises calc silicate, biotite gneisses, schist and granite pegmatite apatite veins belonging to the Pindari Formation3. Above 3800 m asl altitudes, glacial processes dominate and between 3800-2800 m asl glacio-fluvial processes are dominant; below 2800 m asl mainly the fluvial processes are active.

Geomorphologically Mandakini valley (Figure 7) was formed by the erosional and deposional processes of glacio-fluvial origin. The Kedarnath town is situated on the outwash plane of Chorabari and Companion glaciers. The channels of Mandakini and Saraswati Rivers encircles this outwash plane and meet near the Kedarnath town where the outwash plane ends.

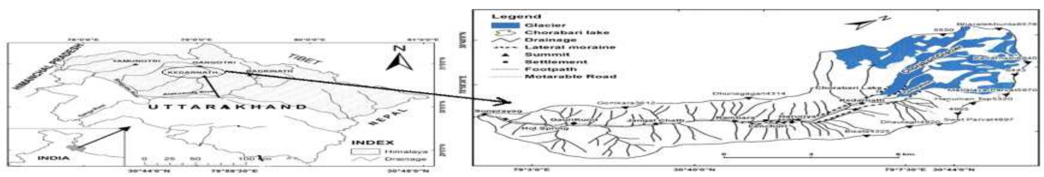

Figure 7: geomorphology of Kedarnath (Gupta ,2013)

These streams cut their banks every year. Overcrowding of the people near the temple led to an artificial change in the course of Sarswati River which now flows just behind the Kedarnath town. This was the major reason for the scale of the disaster.

Desiccation Cracking

The phenomenon of cracking is present in most geotechnical structures and has been of particular interest to civil and mining engineers. Cracks increase by progression as drying increases as shown in the (fig 8). Cracks pose a threat to the integrity of geotechnical structures such as slopes, embankments, dams, tunnels, pavements, foundations, etc. Cracks adversely influence the stability of slopes by:

1. Providing a preferential path to water flow, thereby inducing high pore-water pressures
2. Cracks can form part of the slip surface providing little or no shear strength.
3. Surface cracks formed due to silt deposition on the dam surface have a tendency to progress inwards thus reducing the critical section of the dam.
4. Cracks provide initial route for piping failure
5. Cracks aid in washout during overtopping failure

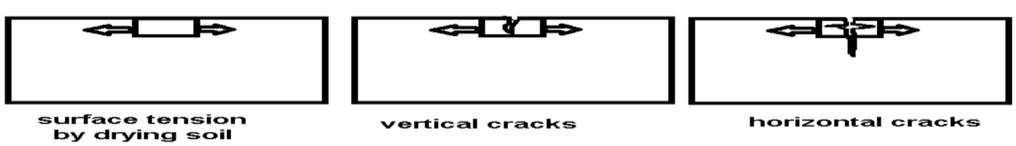

Figure 8: shows Progression of desiccation or shrinkage cracks

Therefore, a clear understanding of the effect of cracks is vital for safe and economical designs of levees, dams and slopes. Traditional design of earth embankments is based on the hypothesis of intact fill, i.e., the presence and occurrence of cracks is disregarded. But under actual conditions, it is unavoidable to prevent cracks formation. Desiccation cracks are formed due to shrinkage of the soil mass as a result of evaporation of water during summer seasons. In the hot summer seasons of India cracking is natural. The phenomenon of desiccation cracking is presumed to increase in future due to global warming, when the range of the extreme temperatures will increase. The total flow increases dramatically with increases in crack size (Figure. 9a)

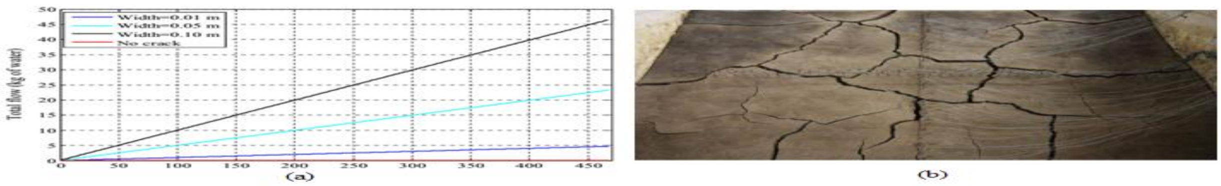

Figure 9: (a) flow v/s cracks (b) Dessication cracks (Khandelwal 2011)

The presence of cracks (fig 9b) makes the soil slopes susceptible to water seepage, erosion, loss of shear strength and consequent failures (Khandelwal 2011)

Loss of storage Capacity of dam: The observed annual percentage loss in gross storage is given in Tables below. The annual percentage loss in gross storage has been worked out as the average based on the data of 239 reservoirs (CWC, 2015). Earlier it was believed that sediment in a reservoir always deposited in the bottom elevations of a reservoir rather than depositing throughout the full range of reservoir depth. It has now fully been established that sediment deposits throughout the depth of reservoir and reduces the capacity of reservoirs at all elevations. The maximum silting takes place at the interface of dam and water.

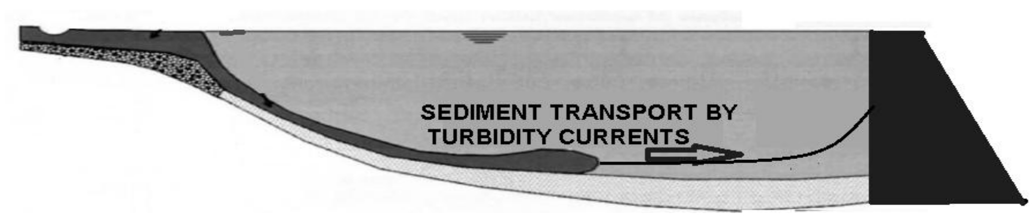

Figure 10: shows transport of sediments in dams

There is an up-wash of bottom sediments against the wall due to back pressure build up and continuity of motion (Figure 10). This causes a bowl shaped bottom that can be seen in various photographs of dried up dams elsewhere in India and internationally too.

In the reservoirs which have small sluicing capacity with respect to normal floods and which have no reservoirs above them, the siltation rate is comparatively high in the first 15-20 years and thereafter it decreases. This is because the obstruction by the dam causes the dips and flanks of the storage basin to fill up with silt in the early years. Besides, the progressive development of deltas above reservoirs helps in trapping some of the silt load (Table 1a & 1b).

These tables show that the reservoir capacity is steadily decreasing. The impact is more on the Himalayan region dams. The silt arrives as a suspension and different particle sizes settle at different rates. The turbidity currents and eddies caused by heat cycle keep much of the silt in suspension. The various sizes and turbulence cause a sub-zones in the reservoir storage zone as shown in the figure below (Figure 11). There is a clear water zone of about one third height, a turbid water zone of one sixth height, a sludge zone of one third height maintained by turbidity currents and the settled sedimentation zone of the balance height. These values are not absolute but vary from dam to dam depending on the properties of the catchment area. They are as seen the tables above (CWC, 2015) the highest for Himalayan region. The values of siltation often record only the bottom zone and ignore the other zones.

Additional Silt Pressures: Normally dams are designed for water pressure on the upstream side. The silt load creates an additional pressure on the water face of the dam. As mentioned earlier the various sizes cause a zonation of the reservoir storage zone. The IS code (IS:6515-1984) gives the following provisions for Consideration of Silt Load. Gravity dams are subjected to earth pressures on the downstream and upstream faces where the foundation trench is to be backfilled. Except in the abutment sections in specific casts and in the junctions of the dam with an earth or rock-fill embankment, earth pressures have usually a minor effect on the stability of the structure and may be ignored. The present procedure is to treat silt as a saturated cohesionless soil having full uplift and whose value of internal friction is not materially changed on account of submergence. Experiments indicate that silt pressure and water pressure exist together in a submerged fill and that the silt pressure on the dam is in proportion of the fill by submergence. Criteria for Design - Horizontal ‘ silt pressure ’ is assumed to be equivalent to that of a fluid with a mass of density of 1360 kg/m^2, and Vertical ‘ silt pressure ’ is determined as if silt equivalent to that of a fluid of mass density of 1 925 kg/m^2. Thus we see that the factors of safety will get considerably reduced due to siltation.

Stability calculation: Himalayan dams as mentioned earlier have a huge silt load almost 3.5 to 5 times that of dams in the rest of India. We will compare the factor of safety for normal dams with no silt load and dams with silt load.

The silt is assumed to be uniformly distributed throughout the height of the water storage during peak rainy season. The following values were adopted for the purpose of calculation.

Height of dam = 15 m; Density of moraine dam =2 Mg/m^3 ; Density of water = 1 Mg/m^3

Density of silty water = 1.75 Mg/m^3

Table 1a: Annual percentage loss of gross, live and dead storage capacity of reservoirs (CWC 2015)

Sl.No.	Description	Minimum	Maximum	Average	Remarks
1	Annual percentage loss of gross storage	0.03	3.38	0.42	Based on average data of 239 reservoirs
2	Annual percentage loss of dead storage	0.007	5.23	0.494	Based on average data of 86 reservoirs
3	Annual percentage loss of live storage	0.003	3.23	0.04	Based on average data of 86 reservoirs

Table 1b: Rate of Siltation of Reservoirs (Region wise) (CWC 2015)

Sl. No.	Region	No. of reservoirs	Median values of rate of siltation	
			Th.cu.m./sq.km/yr	Ha.m./100 sq.km/year
1	Himalayan Region (Indus, Ganga and Brahmaputra basins)	14	1.581	15.81
2	Indo Gangetic Plains	15	0.752	7.52
3	East flowing rivers upto Godavari (Excluding Ganga)	5	0.678	6.78
4	Decan Peninsular east flowing rivers including Godavari and south Indian rivers	115	0.378	3.78
5	West flowing rivers upto Narmada	53	0.861	8.61
6	Narmada and Tapi Basins	10	0.651	6.51
7	West flowing rivers beyond Tapi and south Indian rivers	31	2.1325	21.325

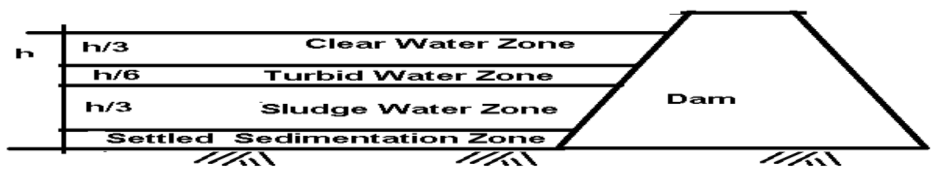

Figure 11: shows different zones in a Dam Storage

The factor of safety against over topping is reservoir volume (reach and depth) dependent. The Chorbari dam was neither designed nor maintained hence there was no safe balance storage volume. We have not calculated the factor of safety against over topping as there was insufficient data available. But as seen in these deliberations siltation reduces the balance storage to zero thus it also reduces the Factor of safety from 1 to nearly zero.

Table 2: Formulas used for calculation of factor of safety

Stability Check	Formula	Notations
Factor of safety against sliding (F_s):	$F_s = \frac{P_r}{P_s}$	P_r = Resisting Force P_s = Horizontal Sliding Force
Factor of safety against overturning (F_o):	$F_o = \frac{M_r}{M_o}$	M_r = Resisting Moment M_o = Overturning Moment
Factor of safety against over topping(F_h)	$F_h = \frac{V_b}{V_f}$	V_f = Volume of Peak Flood Inflow V_b = Balance Storage Capacity Volume

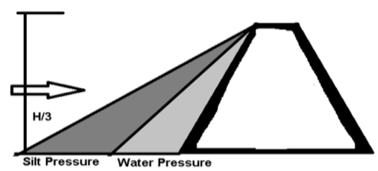

Fig12: schematic Silt pressure diagram

Figure 12: showing schematic silt pressure diagram and table used for stability check for dam

The available commercial software do not adequately provide for silting load on reservoir. The calculations of the factors of safety were hence performed on excel sheets prepared by us. The results are shown below for comparison.

Table 3: of comparison between normal and silt load

Case	F_s (Sliding)	F_s (Over turning)	F_s (Over topping)
normal load	1.5	4.8	0
silt load	1.26	4.39	0

Conclusion

Moraine dams are basically temporary natural earth dams. When these dams are augmented for height without the proper precautions they are in danger of failure. The melting of Chorabari Glacier combined with the cloud burst and the reduced capacity of the dam due to silting up caused a major disaster that was avoidable. The results have shown that there is critical loss of soil when an earth dam fails. The accumulated silt load cascades down the slope carrying with it loose boulders and rock that obliterate everything in their path. Also the bigger the dam, the greater the soil loss and resulting damage. The Government has to take care of these issues in future zoning of such areas.(Dobhal et al 2013) Failure of such dams can lead to catastrophic consequences. The data collected from various sources indicates that the disaster occurred due to reduced reservoir capacity due to siltation, improper compaction as it was a natural blockage and increase in height without spillway provisions. Due to natural formation of the lake there was no proper bondage at the abutment of the moraine with the mountain. This was the weakest spot and was saturated due to the ongoing monsoon season. It was the first to give way during the overtopping caused by reduced reservoir flood absorption capacity due to silting up of the reservoir. The effectiveness of a disaster reduction plans rely on the perception of the disaster itself and what is learnt from such an experience.

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