Dam Break Flood Hazard Assessment: A Case Study for a Small Dam at Source Stream of River Ganga in Uttarakhand, India

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Abstract: Structural measures of a flood defense systems are designed for a specified degree of protection that are defined through the exceedance probability of the flood. However, the failure of major storage structure induces additional flooding risk in the downstream floodplains over and above the specified degree of protection. Hence, the regulating agencies maintains the safety guidelines to include the dam failure while assessing the comprehensive flood risk in the downstream reach. Thus, the dam break analysis evaluates the safety level in the downstream river reach due to flood likely to be induced from storage after the failure of dam with or without the flood generated from meteorological conditions. The comprehensive dam break analysis includes the estimation of the extent and magnitude of flooding, its occurrence time and duration of flooding. The specific flood mitigation measures include preparation of emergency action plans for downstream river reach with computation of available warning time and evacuation plans. The emergency action plans are known to planners, local administrators and even likely to be affected population in priory. The public risk perception helps to develop flood preparedness plan and in efficient risk management strategy. The dam break analysis is essentially a two step procedures, (i) modelling the development of breach in the dam section and computing the breach (flood) outflow, and (ii) routing of flood hydrograph in the downstream river reach to compute the various flood attributes. In this paper, dam break analysis of Dhauliganga dam located in Uttarakhand in Kumaon Lesser Himalayas has been reported. The various scenarios of flooding due to dam breach of the concrete face rockfill dam has been carried out and flood inundation, time of occurrences etc. has been estimated. The hydraulic model for the river reach of about 30 km is developed in MIKE 11 using surveyed river cross sections and 10 m resolution DEM of the study area generated using CARTODEM provided by NRSC, Hyderabad. Three cases of flooding are simulated; (i) flooding due to PMF in the river causing dam break condition; (ii) flooding due to PMF without dam break; and (iii) sunny day failure condition (dam failure with nominal inflow when reservoir is full). It is observed that the time of travel of peak flood from dam site to major settlement area at Dharchula, about 20 km downstream location is 42 minutes for critical case of dam failure. The maximum flood level and time of travel of the peak flood at other important locations are estimated. However, the analysis shows that no settlements/ villages area are under inundation even for most critical flooding conditions. The extent of flood hazard for various cases of flooding are estimated by superimposing the inundation map over Google Earth for detailed description of inundated areas and the infrastructures likely to be affected.

Keywords: Dam break analysis, MIKE 11, Flood inundation, Flood hazard, EAP

1. Introduction

Protection of the public lives and properties from the consequences of dam failures are important as massive population and infrastructure are vulnerable to dam break disasters. The prior assessment of extent, magnitude and time of flooding due to failure of dam/

embankment are the important input in planning for flood preparedness measures. It is quite difficult to conduct analysis and determine the warning time and extent of inundation at the time of disaster. Therefore, pre-determination of these parameters is done by simulating a hypothetical dam break/ embankment failure situation. The dam break flood is different from the storm generated flood in the sense that it hardly gives any response time for emergency action. The sudden and uncontrolled release of stored water, generally coinciding with the catastrophic climatological events raises the flood magnitude to a very high level and thus the water spreads to a wider area in the downstream causing the losses much more as compared to normal rainfall generated floods. Further, with the increase in extremist actions over the objects of national and economic interest, the emergency action plans are prerequisite. Such plans consist of the maps showing the flood inundations under various scenarios of dam failures. This helps in estimating the potential damage. The amount and extent of flooding and occurrence of their time are also included. The threatened settlement, property, and other infrastructures, in addition to emergency rescue plan, communication links etc. are the important constituents of the EAP. The hypothetical dam break analysis is carried out to predict potential flood damage and to prepare emergency action plan (EAP) in advance. Such analysis is mandatory not only for the existing and old dams but also for the proposed dams. (MoEF, 2015)

A complete dam break analysis involves a balanced consideration of hydrological, hydraulic, environmental, and geotechnical and structural parameters pertaining to dam and downstream flood plains. The description of time dependent flood wave propagation, downstream of a breached dam is extremely complex. It is a function of site specific parameters including reservoir characteristics and breaching characteristics of dam. Further, the movement of flood wave across the flood plain will be governed by another range of determinants, many are difficult to replicate in a mathematical model; e.g. dynamic variation in terrain and surfaces, influence of land use change etc. The dam break flood simulations are carried out by developing various scenarios leading to dam failure in addition to re-evaluating the probable maximum flood (PMF), the most general cause of dam failure in natural circumstances. The insufficient capacity of the spillways may be incapable to pass the updated estimate of PMF causing dam failure due to overtop. Another likely reasons for dam failure includes earthquake induced structural failure, equipment failure, criminal action, sabotage etc. (CWC, 2006, EAP)

With the advancement in computational fluid dynamics (CFD) and availability of new tools and techniques like; geographical information system (GIS) and satellite images, some of the difficulties have been successfully accounted for. Several experimental, analytical, and numerical models have been developed to carry out dam break analysis. Computer-aided numerical models such as DAMBRK (Fread, 1988), SMPDBK (Wetmore and Fread, 1991), CADAMBRK (Liong et al., 1991), NWS FLDWAV (Fread, 1993), HEC RAS (USACE, 2006), BOSS DAMBRK (Kho, 2009), and MIKE 11 (DHI, 2004) have been widely used successfully across the world due to their high computational speed and efficiency. Majority of dam break analysis studies have been carried out using 1D model. The NWS DAMBRK model has been used for dam break analysis of Barna dam, Madhya Pradesh, India (NIH, 1997), Ghodahoda project Odisha India (NIH, 2000), and the proposed dam on Yamuna river, India (Lodhi and Agrawal, 2012). BOSS DAMBRK model was used to study the dam break analysis of proposed dam on the Gerugu river Malaysia (Kho et al., 2009). HEC RAS model has been used for dam break analysis of Oros Dam Brazil (Gee, 2008), Danjiangkou and Yahekou dam failures in the Han river China (Minglong and Jayawardena, 2008), and Foster Joseph Sayers Dam in Center Coutry PA, USA (Xiong, 2011). SMPDBK model has been used for dam break analysis of Foster Joseph Sayers Dam in Center Coutry PA, USA (Shahraki et al., 2012). MIKE 11 model has been used for dam break analysis of Bichom and Tenga dam (Husain and Rai, 2000), Buffalo Creek Dam, North Carolina, USA (Tingsanchali and Chinnarasri, 2001), Indra Sagar and Omkareshwar project, India (Pillai et al., 2012), Hirakud dam, India (Mohite et al., 2014). 1D models, though simple to use and provide information on bulk flow characteristics, fail to provide detailed information regarding the flow field. Hence, attempts have been made to model the 2D nature of floodplain flow. A 1D approach is used to describe breach growth and breach flow and a 2D approach is used to predict flood propagation in the inundated areas. In this paper, a case study of failure of Dhauliganga dam located in Uttarakhand in Kumaon Lesser Himalayas has been reported. The project is maintained by NHPC Limited and has provided all the relevant data required for the study. The study envisages the identification of various scenarios of flooding, estimation of breach parameters, modelling of dam break flood and its routing in the downstream reach to compute the maximum flood inundation and its time of occurrences. The failure of Dhauliganga dam has been simulated in MIKE-11 model. The movement of flood in the downstream reach is solved through Saint-Venant equations using 6-points Abbott scheme in MIKE 11 (DHI, 2004). The breaches is modeled by means of a “dam break” structure and its development is described by time series for breach width, crest level and side slope. The maximum flood level and its time of occurrence and flood warning time have been estimated at important locations. The extent of maximum inundation for various cases of flooding has also been computed.

Figure-1: Index map of study area

2. Study Area

The Dhauliganga dam is located on river Dhauliganga, a tributary river of Kali in Pithoragarh district of Uttarakhand in Kumaon, Lesser Himalayas as shown in Figure-1. The river originates in the high Himalayan mountain from the glaciers at an elevation of about 5160 m. It flow in the South-Southeast direction and meet river Kali which is also called as Sharada river in its downstream stretch (from Tanakpur onwards). The catchment area of river is about 1372 Km^2 with average relief of the river slope of the order of 48 m for every l Km length. Dam is 56 m high above the river bed level is a concrete face rockfill embankment dam. The length of reservoir is about 1.4 km, elevation of dam crest is RL 1352.0 m and length of the crest is 270 m. The full reservoir level (FRL) of the reservoir is at RL 1345.0 m and minimum draw down level (MDDL) is at RL 1330.0 m. Two gated spillway are located on the right flank of the dam with open chute and flip bucket (10 m x 6 m) with total discharge capacity of 3210 m^3/s. The power house is located at about 9.75 km while one major settlement, Dharchula, is located at about 21 km downstream of dam site. Another major settlement is village Dhap located about 30 km downstream of dam site. The river cross sections are extracted from CartoDEM while other related data for the dam and reservoir are also obtained from the project authority.

3. Methodology

Several commercial software like NWS DAMBRK, HECRAS, and MIKE 11 models are available for carrying out the dam break modeling. All these software essentially carry out hydrodynamic modelling involving solution of the basic St. Venant's partial differential equations of conservation of mass and momentum as shown below:

i. Conservation of mass (continuity) equation

$$(\partial Q/\partial X) + \partial(A + A0) / \partial t - q = 0 \quad (1)$$

ii. Conservation of momentum equation

$$(\partial Q/\partial t) + \{ \partial(Q2/A)/\partial X \} + g A ((\partial h/\partial X) + S_f + S_c) = 0 \quad (2)$$

where, Q = discharge; A = active flow area; A0 = inactive storage area; h = water surface elevation; q= lateral outflow; x = distance along waterway; t = time; S_f = friction slope; S_c = expansion contraction slope and g = gravitational acceleration.

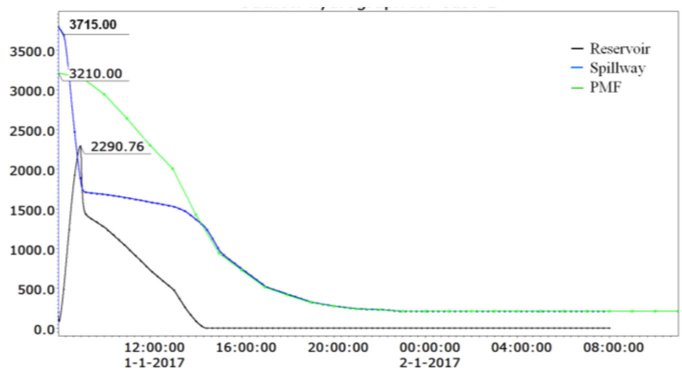
The mathematical modeling of dam break flow is a cost and time effective approach to (approximately) solve the above governing equations. The present dam break study has been carried out using MIKE 11 HD model developed by Danish Hydraulic Institute (DHI). The core of the MIKE 11 system consists of the HD (hydrodynamic) module, which is capable of simulating unsteady flows in a network of open channels. The results of a HD simulation consist of time series of water levels and discharges. MIKE 11 hydrodynamic module is an implicit, finite difference model for unsteady flow computation. The model can describe sub-critical as well as supercritical flow conditions through a numerical description which is altered according to the local flow conditions (in time and space). The Dam Break Module in MIKE 11 simulates the outflow hydrograph resulting from the failure of a dam.

Breach Parameter Estimation - The parameters of the breach are given as a time series in the boundary editor. The time is relative to the start of the breach. Between the specified times the parameters are linearly interpolated. The NWS DAMBRK method simulates the failure by two methods; Breach failure and Piping failure. The breach failure uses a weir type equation to determine the flow through the breach where as the latter is based on an orifice type equation. Both methods rely on the user specifying the full development of the breach geometry as a function of time. The estimation of the breach location, size, and development time are crucial in order to make an accurate estimate of the outflow hydrographs and downstream inundation. Many case studies have been performed on data from historic dam failures, leading to guidelines, regression equations, and computer modeling methodologies for prediction of the dam breach size and time. Tony Wahl (1988) summarized a comprehensive literature on historic dam failures data and recommends range of breach parameter for dam break analysis. The Federal Agencies guidelines and regression equation based approach are widely used. In fact the guideline provides the upper and lower bound of parameters values while the range estimated from regression equations are used for parameter sensitivity analysis (TD-39, 2014). The estimated breach parameters for the dam is shown in Table-1.

Table-1: Description of breach parameters

SN	Approach	Average Breach width (m)	Time of failure (hour)	Side slope of breach section
1	Froehlich (1995)	66	0.26	1.4:1
2	Froehlich (2008)	52	0.25	1.:1
3	MacDonald and Langridge-Monopolis (1984)	310	2.82	0.5:1
4	Von Thun and Gillette (1990)	128	1.13	1.:1.
5	Xu and Zhang (2009)	27	1.9	0.5:1
6	Upper bound	28	4	1:1
7	Lower bound	225	0.1	1:1
8	Estimated breach parameters	50	1	1:1

4. Analysis and Results



In addition to dam break flood of Dhauliganga dam and extreme flood in Dhaliganga river, the extreme flood in Kali river has also be a major flooding source for the downstream river reach. Hence, the extreme flood of Dhauliganga and Kali river have also been considered in the dam break analysis. The Dhauliganga/Kali stream from Dhauliganga dam to the Baluakot, a stretch of about 30 km from dam site, has been simulated in MIKE 11. The river cross sections extracted from CartoDEM have been used in the MIKE 11 model setup. The design flood of PMF and 100 year return period flood is defined in the Dhauliganga reservoir in different cases of flood simulation. The dam fails when dam is at MWL of 1348.5 m and design flood enters into it. The failure through overtopping of dam is considered. Further, during time of failure all the spillway gates are considered to remain fully open. The downstream boundary condition is defined at Chainage 30 km of Dhauliganga/Kali river. The breach starts at RL 1348.5 m (MWL) and develop in trapezoidal shape and the bottom of the section come down to the lowest bed level of RL 1307 m (crest level of chute spillway) in duration of 1 hour. The estimated breach parameters for Dhauliganga dam are; breach width = 50 m, time of failure =1 hour and side slope of trapezoidal breach section = 1H: 1V. The estimated breach parameters are within the upper and lower range suggested by federal Agency Guidelines. Moreover, the sensitivity of breach parameters has been carried out for the computed range.

Figure-2: Inflow design flood and outflow hydrograph at dam section.

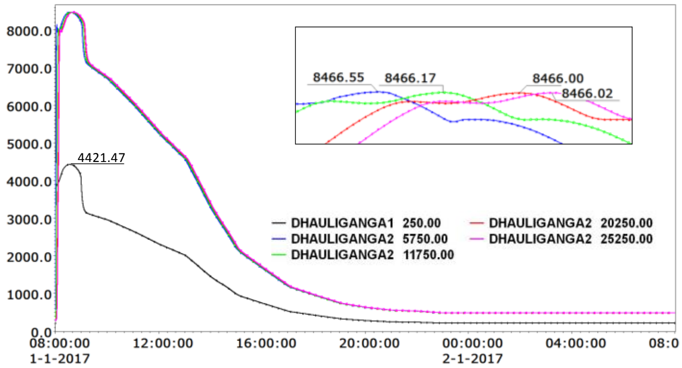
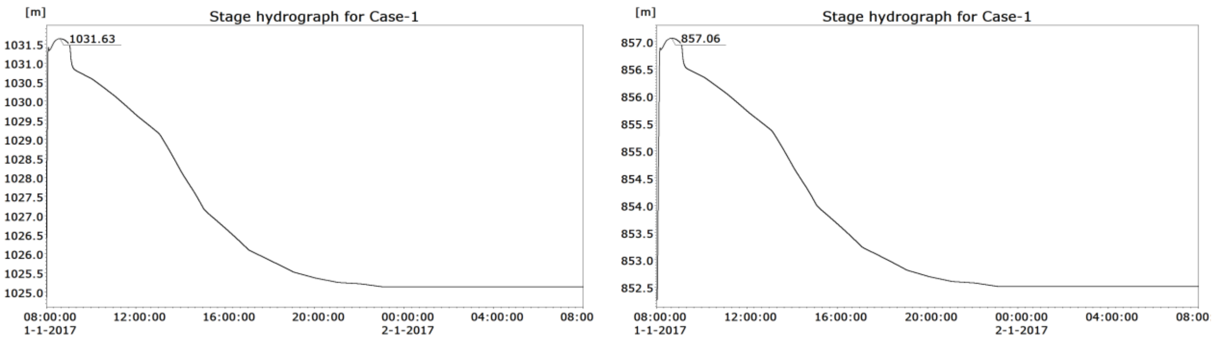


Figure-3: Attenuation of flood hydrograph

For dam break analysis, the most critical flooding scenario is considered when reservoir is at FRL, i.e. at RL 1345.0 m and peak of PMF flood enters into reservoir considering all spillway gates to be fully open. Due to inflow flood, when reservoir level rises above FRL, the breach starts. The outflow from breach section and spillway section for this flooding scenario is shown in Figure-2. The figure shows peak flood from breach section and spillway gates are 2290.76 m^3/sec and 3715.00 m^3/sec respectively. In dam break analysis, the instance when peak of PMF enters into reservoir causing reservoir at FRL, the breach is considered to initiate. Hence the peak of hydrograph start from the instant of start of breach. The initiation of breach time is 8.00 AM on 01-01-2017 and develops to its complete size at 9:00 AM and the peak flood from breach section occurs at 8:57 AM. However, the peak flow from spillway occurs at 8.00 AM only when the reservoir level is maximum and all gates are fully opened. As the downstream river valley is very narrow and steep, the attenuation of flood hydrograph is hardly noticed. In the downstream reach, Kali river also joins the flow of Dhauliganga river at 4.6 km downstream of dam site. Therefore the peak of flood hydrograph decreases slightly in the downstream reach only upto the confluence due to attenuation but suddenly increases further downstream due to inflow from Kali river. The flood attenuation is shown in Figure-3. At Chainage 250 m, 5750 m, 11750.0 m, 20250.0 m, and 25250 m, the peak flood of 4421.47m^3/sec, 8466.55 m^3/sec, 8466.17 m^3/sec, 8466.0 m^3/sec, and 8466.02 m^3/sec, occurs at 8:34 hour, 8:36 hour, 8:38 hour, 8:42 hour, and 8:43 hour respectively. Though, while propagating in the downstream direction, the flood hydrograph peaks are more or less constant. The reason may be attributed to several factors including; initial residual discharge resulting from hotstart file (dam break model requires a hotstart file so that the river is not dry in the initial stage), very steep and gorge type river valley wherein within very insignificant/ no valley storage is permitted, lateral flow from Kali river in the Dhauliganga river etc. Hence, the time of occurrence of peak flood at 25 km d/s reach from the dam site is only about 43 minutes from start of the breach for this flooding condition.

The water surface profile for DB flood is computed. The stage hydrographs at power house and Dharchula are shown through Figure-4. The Dhauliganga power house is located at Chainage 9.75 km while the Dharchula Township is located at Chainage 21 km. The maximum flood levels at these locations are RL 1031.63 m and 857.06 m respectively. Further, the inundation map for the flooding scenario is developed from MIKE 11 result file. The maximum flood elevation maps are superimposed over the high resolution Google Earth image to prepare the inundation maps. The inundation map for DB flood near Dharchula is shown in Figure-5.



9.75 km (Power house) 21 km (Dharchula)

Figure-4: Stage hydrograph for DBA at various chainage downstream of dam

Figure-5: Synoptic view of flood inundation over Google Earth for dam break flood.

Emergency Action Plan

The maximum flood level, extent of inundation and time of flood (flood above a threshold level at a particular location defined locally based on the site condition) are important input for preparing emergency action plan during disaster. The extent and magnitude of maximum inundation (flood depth) depends upon the peak flood level and flood plain topography. For a flooding scenario, the flooding depth at a location depends upon the ground elevation at that location and thus is a localised phenomenon. The flood level (mean sea level) is influenced by the topography of the entire inundated area and thus is more global and representative in quantifying flood events along with the area of inundation. The important locations in the downstream reach of the Dhauliganga dam are Dhauliganga power house and Dharchula Township, at which the maximum flood elevation (msl) has been computed for various cases of flooding. For critical DBF, the maximum flood elevation at Dhauliganga power house and Dharchula Township are RL 1032.0 m and RL 857.3 m respectively. Similar type of flood simulation have also been carried out for various combination of inflow design flood and dam break condition as shown in Table-2. The peak flood level and its occurrence time are estimated at important locations are also shown in this table. The time of occurrence of maximum flood level is shown within bracket. The maximum flood level occurs at Power house is RL 1031.63 m while the elevation of service bay and machine hall at Dhauliganga power house is RL 1039.5 m. Hence, the important plant installations are above the maximum flood level. Further, the maximum flood level is computed at Dharchula is below the danger level, the slope stability and river bank erosion are the major issues in the region due to very steep slope and fragile geological formation (Paudel et al., 2013). The time of travel of peak flood from dam site to a Dhauliganga power house is 38 minute for Case-1. Under pre project scenario, the maximum flood level due to critical condition of flooding (Case-2) is RL 1031.36 m. In this case, the time of travel of peak flood is 4 minutes due to steep river slope. As, the travel time is very small, an effective public warning system is proposed to prevent any casualty.

Table-2: Maximum flood level at important locations for various cases of flooding.

Particulars	**Maximum inundation area (ha)**	**Important locations**	
		Power house	**Dharchula**
MIKE 11 Chainage (km)		9.75	20
Case-1 (PMF flood and dam break)	163.27	1031.63 m 38 min	857.06 m 42 min
Case-2 (PMF flood only)	156.39	1031.36 m 40 min	856.87 m 45 min
Case-3 (only dam break)	94.53	1026.95 m 1 hr 6 min	853.84 m 1 hr 12 min
Case-4 (100 years return period flood)	122.64	1028.90 m 56 min	855.19 m 1 hr 5 min

(Time in bracket shows the time of travel of peak flood from dam site to important locations)

4. Conclusions & Recommendations

For DBF the maximum flood level at Power house and Dharchula are computed as RL 1031.63 m and RL 857.06 m, respectively. The elevation of service bay and machine hall at Dhauliganga power house is RL 1039.5 m and hence above the dam break flood level. However, the time of travel of peak flood from dam site to a Dhauliganga power house is 38 minute only. Further, the computed dam break flood level at Dharchula is lower than the danger level, slope stability and river bank erosion are the major issues in the region due to very steep river slope, valley area and fragile geological formation.

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