Print ISSN : 0972-8813
e-ISSN : 2582-2780

[Vol. 20(2), May-August, 2022]

Pantnagar Journal of Research

(Formerly International Journal of Basic and Applied Agricultural Research ISSN : 2349-8765)

G.B. Pant University of Agriculture & Technology, Pantnagar

PANTNAGAR JOURNAL OF RESEARCH

Vol. 20(2) May-August, 2022

CONTENTS

Sensitivity analysis of breach width parameter of Ramganga dam, using 2D HEC-RAS

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ABSTRACT: Dams have been built for many reasons such as irrigation, hydropower, flood mitigation and water supply to support the sustainability of humanity since the golden age. However, if huge amounts of water are released during the dam breach unexpectedly, it may adversely impact the downstream population and ecosystem. The prediction of the dam's breach geometry is crucial in studies of dam breaking. The hydrograph characteristics of the flood resulting from breaching of the dam mainly depend on the geometry of the breach and the formation time of the breach. The sensitivity analysis was performed on the Ramganga dam which is located in Pauri Garhwal district of Uttarakhand, its latitude and longitude are 29^{0}31'10"N, 78^{0}45'31"E to assess the effect of breach width on the resulting flood hydrograph. HEC-RAS model was used to calculate the effect of breach width on flood hydrograph. In the present study the breach width (Bavg.) was increased and decreased by 25%, 50% and 75%, respectively. Flood hydrograph was estimated at five different locations: Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad, located at 2.5 km, 16.9 km, 25.4 km, 61.2 km and 94.5 km downstream of Ramganga dam, respectively. Sensitivity analysis was performed with Froehlich method with the mode of overtopping failure and maximum operating level at 365.3 meters above sea level. It has been observed from the results of sensitivity analysis that the percent change in peak discharge is high corresponding to breach width i.e., peak discharge is directly proportional to breach width.

Key words: Dam breach, HEC-RAS, sensitivity analysis, Ramganga dam

Dams provide many benefits to civilization; however, floods resulting from dam breach could lead to tremendous loss of lives and properties. Dam failures can be caused by overtopping of a dam due to insufficient spillway capacity and insufficient free board throughout large inflows to the reservoir, seepage or piping (internal erosion), settlements due to slope slides on the upstream or downstream faces of the dam body, liquefaction of earthen dams due to earthquakes, dam foundation failure, Equipment malfunction, Sabotage, etc. (USACE, 2007). Dam breaching can be summarized as a partial or catastrophic failure of the dam resulting in a rapid release of water from the reservoir. Dam failure analysis helps in providing warnings to the public. Keeping all these in view, the analysis of dam breach and inundation maps preparation is very important. Dams are complex structures that are subjected to many forces that can cause failure. One of the forces that cause failure is overtopping. Regardless of the reason, almost all failures begin with a breach formation. The breach is defined as the opening formed in the dam body that leads the dam to fail and this phenomenon causes the reservoir of water behind the dam to propagate towards downstream regions.

The failure of Baldwin Hills Dam, California in 1964 and Lower Van Norman Dam, California due to the earthquake in 1971 provoked the dam authorities to prepare inundation maps for dam failures. Consequently, the requirement for investigating techniques to assess the breach hydrograph came into existence. Numerous dam failures that occurred in The United States during the 1970s motivated researchers to focus much on dam safety (Wu *et al.*, 2011). The study of over 1065 earthen dam failures reveals that significant causes of earthen dam failure are overtopping and piping. Spillways, downstream slopes and foundations are the potential locations at risk for overtopping failure, whereas for the piping failure entire dam section is at potential risk (Zhang *et al.*, 2009).

Many researchers have compared one and two-dimensional hydraulic models, among which Hydrological Engineering Centre – River Analysis System (HEC-RAS) was the most commonly used model for dam breach analysis (Rendon *et al.*, 2012) because of its reliable prediction and the fact that it is an open-source tool. Researchers have also preferred using HEC-RAS model for flood simulation as it gives accurate results, even though the complex channel geometry and bed discontinuity exists by approximation, which poses significant challenges in more robust unsteady hydraulic models. HEC-RAS was developed by the United States Army Corps of Engineers (USACE) to manage and control rivers, channels and other public works. HEC-RAS software provides simulations like one-dimensional steady flow, two-dimensional unsteady flow and coupling of one and two-dimensional unsteady flow, sediment transport and bed load computations.

Most of the models do not directly simulate the breach; instead, the user must determine the ultimate breach parameter and the time required for breach formation. After providing the inputs to the hydraulic model, it then progressively simulates the breach development. Ultimately, the breach parameter are estimated using various empirical equations developed based on the dam and reservoir characteristics such as dam height and storage volume (Wahl, 1997).

The primary objective of this study is to perform dam breach analysis for the Ramganga dam to predict the percent change in peak flood discharge along with the time of occurrence at five places including Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad which are located at 2.5 km, 16.9 km, 25.4 km, 61.2 km and 94.5 km, respectively downstream of the Ramganga dam. These places are chosen based on the maximum population.

Salient features of HEC-RAS

a) HEC-RAS has a graphical user interface programmed in Visual Basic.
b) HEC-RAS is a two-dimensional steady flow model, intended for computation of water surface profile.
c) Modules for unsteady flow simulation and movable-boundary sediment transport calculations are also included.
d) The system is capable of modelling subcritical, supercritical, and mixed-flow regimes for streams consisting of a full network of channels or a single river reach.
e) This current version of HEC-RAS gains new ability to perform 2D hydrodynamic modelling.

MATERIALS AND METHODS

Study area

The Ramganga dam, also known as the Kalagarh dam, is an earth and rock-fill embankment dam on the Ramganga River which is 3 km upstream of Kalagarh in Pauri Garhwal district, Uttarakhand, India. The dam is owned and operated by the Irrigation Department, Government of Uttar Pradesh. The location of the Ramganga dam site is shown in Fig. 1. It is located within the Jim Corbett National Park and has latitude and longitude of 29°31'13"N and 78°45'35"E respectively. The Kalagarh dam is a part of the Ramganga Multipurpose Project, considering to serve as a source for irrigation and for generating hydroelectric power. Construction of the dam began in 1961 and was completed in 1974. The command area of the project is 57,500 ha and the installed capacity of the power station is 198 MW. The dam is 128 meters in height and 630 m in length with a reservoir capacity of 2447 Mcum. The normal and maximum storage levels of the Ramganga reservoir are 365.30 m and 366.20 m.

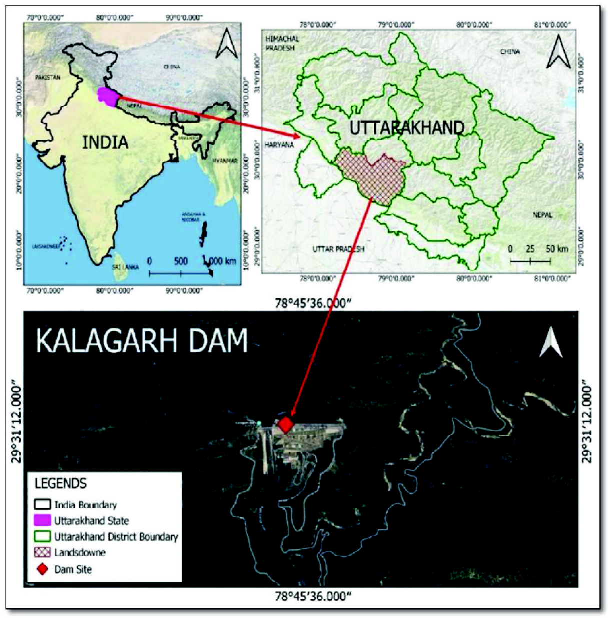

Fig. 1.0: Location of Study Area

Data required for modeling

The selection of modeling depends on the usefulness and requirement of the work. For dam breach analysis accurate and detailed knowledge of the dam, its hydraulic structure and prediction of breach parameter is required. In this work data is collected from the dam authority of Ramganga dam. The details of data used in this two-dimensional work are as given below:

- Digital Elevation Model (DEM) of the Ramganga dam site (Bhuvan portal).
- Salient features of the dam and its hydraulic structures (Irrigation department, Uttarakhand).
- Design flood hydrograph or probable maximum flood as upstream boundary condition.
- Manning's roughness coefficient value of the site (Chow, 1959).
- Normal depth at downstream of the dam used as downstream boundary condition.

HEC-RAS 6.2 model, released on March 11, 2022 is used for the analysis. HEC-RAS was developed by the U. S. Army Corps of Engineers. The model simulates the resulting flood wave generated based on the consequences of an upstream event and models the downstream effect based on the result of dam breach. Embankment dam failure analyses can be viewed as a two-step process. First, the actual dam breach must be analyzed. Second, the breach outflow must be routed to the downstream to determine the resulting downstream flood. The simulation process used in 2D HEC-RAS for dam breach modeling and sensitivity analysis is presented in Fig. 2. The 2D Saint Venant equation which can be obtained from Reynold Navier Stoke Equation by depth averaging method and assuming hydrostatic pressure distribution and small channel slope are used and shown below:

- Conservation of mass:

$$\frac{h}{t} + \frac{(h.u)}{x} + \frac{(h.v)}{x} = 0 \qquad \dots (2.1)$$

- Conservation of momentum

$$\frac{h.u}{t} + \frac{(h.u^2+0.5gh^2)}{x} + \frac{(h.v)}{y} = 0 \qquad \dots (2.2)$$

$$\frac{h.v}{t} + \frac{(h.v^2+0.5gh^2)}{x} + \frac{(h.u)}{y} = 0 \qquad \dots (2.3)$$

The simplest approach to breach parameter prediction modeling is by estimating the breach parameter using various empirical formulae as given by many researchers including Froehlich (1995), Froehlich (2008), Von Thun and Gillette (1990), MacDonald and Landgridge (1984) and then comparing their result with guidelines given by different agencies such as USACE, National Weather Service (NWS), and Federal Energy Regulatory Commission (FERC). After complete analysis and calculation, Froehlich (2008) breach parameters are considered and USACE 2007 guidelines are used in this work with an overtopping failure mode.

Sensitivity analysis

Sensitivity analysis is carried out by varying the breach width of the breach parameter as obtained from Froehlich's (2008) equations by 25%, 50% and 75% respectively while keeping the remaining parameters constant to understand their impact on peak flow (Xiong, 2011; Sidek and Ros, 2011).

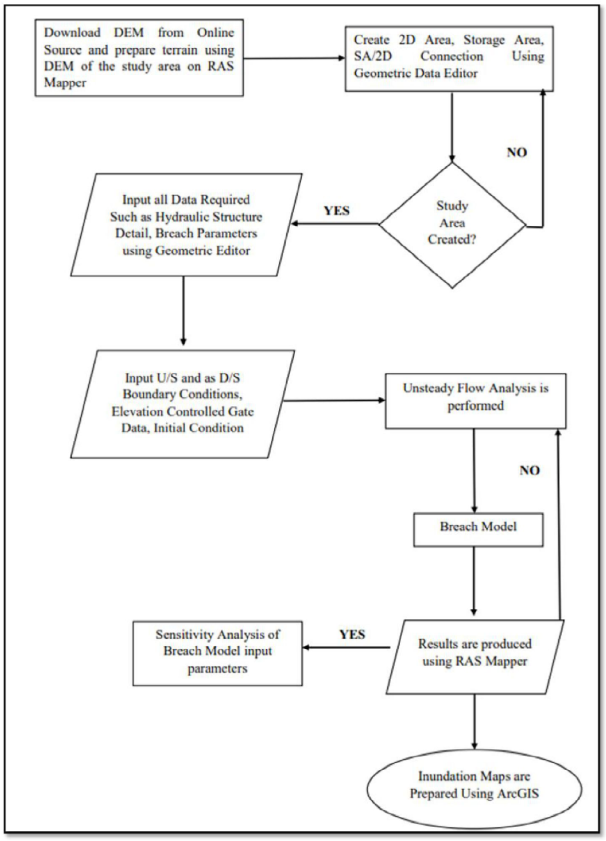

Fig. 2: Flowchart representing 2D dam breach modelling and sensitivity analysis

RESULTS AND DISCUSSION

The results are developed after hypothetical breach modeling of the Ramganga dam by using 2D HEC-RAS and the flow hydrographs are compared at five places downstream. Tables 1, 2, 3, 4 and 5 represents the per cent change in values of peak flow and the time of occurrence whereas Figures 3, 4, 5, 6 and 7 represents the peak flow corresponding to variation in breach width.

Table 1: Summary of the % change in Q and T_{Qmax} for varying breach width (B) at Kalagarh

KALAGARH						
B(meter)	% B diff.	Q_{max}(cumec)	% Q_{max}	T_{Qmax}(minutes)	% T_{Qmax}	NOTE
612.5	75	178510.08	29.74	2:20	-22.22	A+75%
525	50	165861.14	20.55	2:30	-16.67	A+50%
437.5	25	152658.70	10.95	2:40	-11.11	A+25%
350	0	137590.91	0	3:00	0	Original (A)
262.5	-25	121029.56	-12.04	3:10	5.56	A-25%
175	-50	102046.25	-25.83	3:40	22.22	A-50%
87.5	-75	79203.46	-42.44	4:10	38.89	A-75%

Table 2: Summary of the % change in Q and T_{Qmax} for varying breach width (B) at Harewali

HAREWALI						
B(meter)	% B diff.	Q_{max}(cumec)	% Q_{max}	T_{Qmax}(minutes)	% T_{Qmax}	NOTE
612.5	75	171141.27	27.68	3:10	-17.39	A+75%
525	50	160053.02	19.41	3:20	-13.04	A+50%
437.5	25	147834.17	10.29	3:30	-8.70	A+25%
350	0	134037.75	0	3:50	0	Original (A)
262.5	-25	118276.38	-11.76	4:20	13.04	A-25%
175	-50	99759.84	-25.57	4:40	21.74	A-50%
87.5	-75	74604.70	-44.34	5:10	34.78	A-75%

Table 3: Summary of the % change in Q and T_{Qmax} for varying breach width (B) at Afzalgarh

AFZALGARH						
B(meter)	% B diff.	Q_{max}(cumec)	% Q_{max}	T_{Qmax}(minutes)	% T_{Qmax}	NOTE
612.5	75	170113.91	27.34	3:20	-16.67	A+75%
525	50	159277.95	19.23	3:30	-12.50	A+50%
437.5	25	147376.94	10.32	3:40	-8.33	A+25%
350	0	133591.42	0	4:00	0	Original (A)
262.5	-25	118031.03	-11.65	4:20	8.33	A-25%
175	-50	99302.55	-25.67	4:40	16.67	A-50%
87.5	-75	73916.76	-44.67	5:20	33.33	A-75%

Table 4: Summary of the % change in Q and T_{Qmax} for varying breach width (B) at Dilari

DILARI						
B(meter)	% B diff.	Q_{max}(cumec)	% Q_{max}	T_{Qmax}(minutes)	% T_{Qmax}	NOTE
612.5	75	96410.55	14.92	7:50	-11.32	A+75%
525	50	94670.66	12.84	8:10	-7.55	A+50%
437.5	25	90051.93	7.33	8:30	-3.77	A+25%
350	0	83895.94	0	8:50	0	Original (A)
262.5	-25	75447.49	-10.07	9:30	7.52	A-25%
175	-50	63519.83	-24.29	10:30	18.87	A-50%
87.5	-75	46235.89	-44.89	13:00	47.17	A-75%

Table 5: Summary of the % change in Q and T_{Qmax} for varying breach width (B) at Moradabad

MORADABAD						
B(meter)	% B diff.	Q_{max}(cumec)	% Q_{max}	T_{Qmax}(minutes)	% T_{Qmax}	NOTE
612.5	75	56889.40	8.87	12:40	-8.43	A+75%
525	50	56388.55	7.91	12:50	-7.23	A+50%
437.5	25	54691.52	4.67	13:20	-3.61	A+25%
350	0	52252.98	0	13:50	0	Original (A)
262.5	-25	48647.25	-6.90	14:50	7.23	A-25%
175	-50	43096.33	-17.52	16:00	15.66	A-50%
87.5	-75	34258.08	-34.44	19:10	38.55	A-75%

Based on results in Table 1, 2, 3, 4 and 5, it can be noticed that the peak discharge increased when the breach width is increased and vice versa, i.e., peak discharge is directly proportional to the breach width.

A 25 % reduction in breach width (B to 0.75 B) resulted in 12.04%, 11.76%, 11.65%, 10.07% and 6.90% reduction in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad. Whereas, a 25 % increase in breach width (B to 1.25B) resulted in 10.95%, 10.29%, 10.32%, 7.34% and 4.67% increase in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad.

A 50 % reduction in breach width (B to 0.50B) resulted in 25.83%, 25.57%, 25.67%, 24.29% and 17.52% reduction in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari

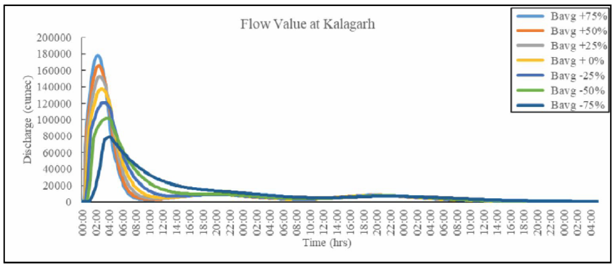

Fig. 3: Peak discharge versus time for varying breach width at Kalagarh

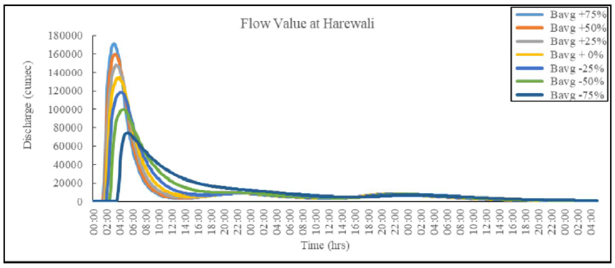

Fig. 4: Peak discharge versus time for varying breach width at Harewali

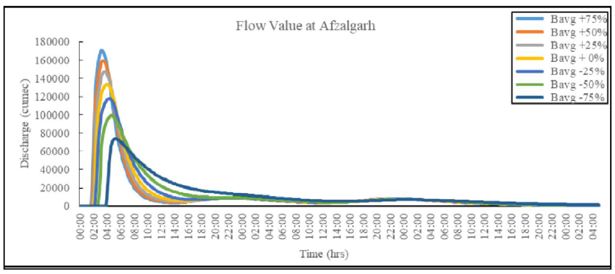

Fig. 5: Peak discharge versus time for varying breach width at Afzalgarh

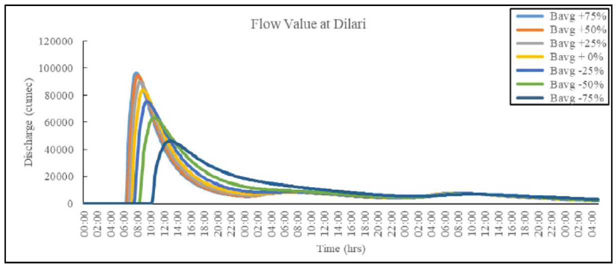

Fig. 6: Peak discharge versus time for varying breach width at Dilari

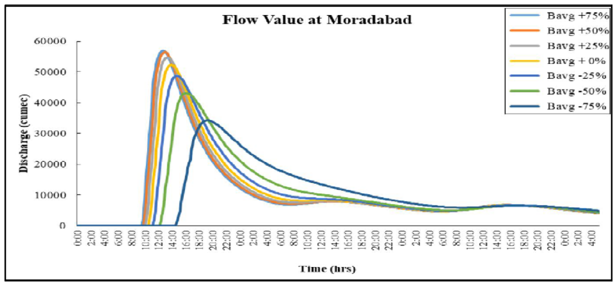

Fig. 7: Peak discharge versus time for varying breach width at Moradabad

and Moradabad. Whereas, a 50 % increase in breach width (B to1.50 B) resulted in 20.55%, 19.41%, 19.23%, 12.84% and 7.91% increase in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad.

A 75 % reduction in breach width (B to 0.25 B) resulted in 42.44%, 44.34%, 44.67%, 44.89% and 34.44% reduction in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad. Whereas, a 75 % increase in breach width (B to 1.75 B) resulted in 29.74%,

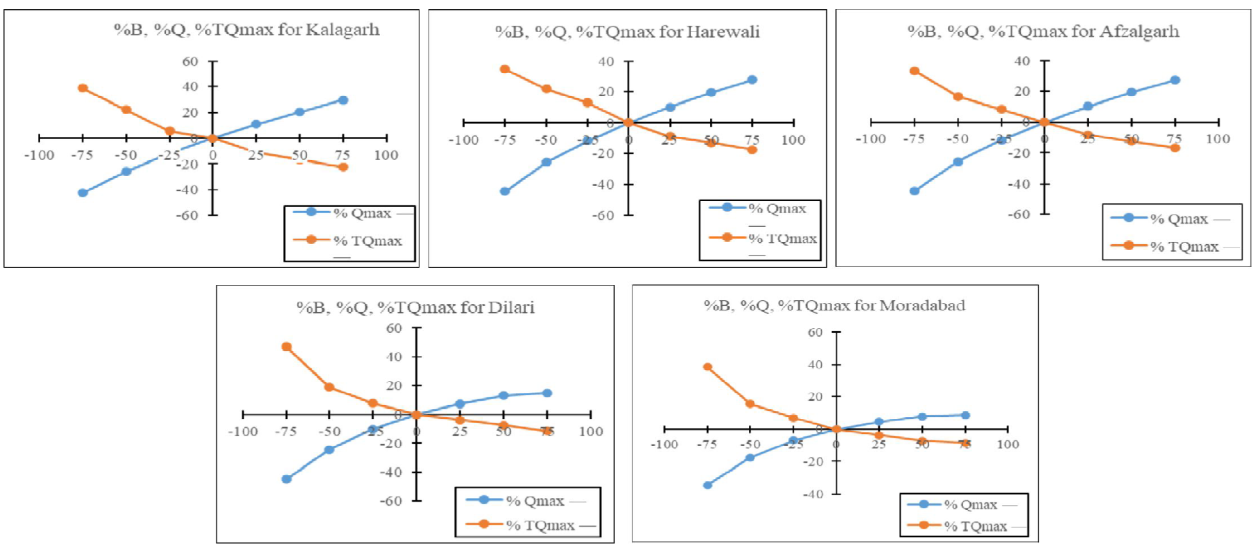

Fig. 8: Line graph between %B, %Q and % T_{Qmax} at different five locations downstream of Ramganga dam

27.68%, 27.34%, 14.92% and 8.87% increase in peak discharge at Kalagarh, Harewali, Afzalgarh, Dilari and Moradabad.

From the results, the rate of change in peak discharge relative to the change in breach width, by 25%, 50% and 75%, has been observed proportional to breach width. The line graph between the percentage peak flows, percentage of time of peak flow and percentage change in breach width is shown in the Figure 8.

CONCLUSION

A dam could fail due to various causes such as piping, overtopping, foundation and many others. In the case of dam breach modeling, it is important to predict the breach parameter accurately. Prediction is limited by the number of reported and analyzed cases. The analysis is done to know the sensitivity of peak flow to breach width. It has been concluded from the results of the sensitivity analysis that the peak flow is highly sensitive to the breach width i.e., the peak flow is directly proportional to breach width. A very small change in breach width shows a very large change in the value of peak flow.

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Received: August 11. 2022
Accepted: August 25, 2022