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Dam-Break Modelling of Rangpo Dam and Rongli Dam for the Chuzachen Hydroelectric Project and Flood Inundation Mapping of Post Dam-Break Scenario

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Abstract:

When a dam-breaks, it could be as highly devastating as any other natural flood hazard that propagates downstream depending upon the impounded volume of flow. The case study of the Chuzachen Hydroelectric Project (HEP), Sikkim, India has been demonstrated in this paper. The dam-break modelling of Rangpo Dam and Rongli Dam, which are the major components of the Chuzachen HEP, have been presented. The Rangpo Dam is located on the Rangpo River (Rangpo Chu) near Sisney Village, whereas the Rongli Dam on the Rongli River (RongliKhola) at the foot of Lamaten village. The project has one powerhouse at the foot of Chuzachen village near the confluence of the Rangpo River and Rongli River near Rongli town. The project is planned to abstract runoff from both the reservoirs of Rangpo Dam and Rongli Dam through headrace tunnels taking off from each reservoir, and then these tunnels join together to form a single tunnel downstream.

Two independent one-dimensional physically-based numerical models have been developed for the Rangpo River and Rongli River using the well-recognized software, HEC-RAS. The dams have been included as inline structures in the respective models. The modelling criteria have been set up to develop the models. The models have been simulated for various dam-break scenarios to analyze the consequence of the dam-break event. The resulting flood hydrographs from each model have been interpreted. The impact of the flood downstream due to the dam-break in terms of flood extent has been displayed on flood inundation maps.

Keywords:*Dam-break, Chuzachen HEP, one-dimensional, inundation, mapping, reservoir.*

1. Introduction

The purpose of any engineered structure, such as a dam, is defeated when the risk of dam-break is unaddressed. The widely known potential causes of dam-break are flow overtopping the dam, piping failure, and unforeseen sabotage. All the causes are none other than risks and may lead to the failure of the dam either instantaneously or at intervals due to human errors or/and natural disasters. Both cases need preparedness to deal with them. For example, in the year 2023, the Teesta-III dam-break in the state of Sikkim, India, due to the glacial lake outburst flood (GLOF) of the upstream lake - South Lhonak glacial lake, was heavily criticized for being unprepared for such eventualities causing devastation of life and property downstream. The complete failure of this hydropower project raised the alarm for all dam authorities and owners to be extra-vigilant and be ready with a remedial plan for disaster management due to a dam-break. Therefore, a strategic approach towards the dam-break study needs to be undertaken as a first and mandatory step whenever a dam is envisioned for any project.

1.1 Dam-break Case Study

The case study of the Chuzachen Hydroelectric Project (HEP) has been demonstrated, where the dam-break modelling works were completed in the past using physically-based numerical models, thereby displaying the inundation mapping and flood extents. In this paper, the dam-break modelling of Rangpo Dam and Rongli Dam, which are the major components of the Chuzachen HEP, have been presented. The Rangpo Dam is located on the Rangpo River (Rangpo Chu) near Sisney Village, whereas the Rongli Dam on the Rongli River (RongliKhola) at the foot of Lamaten village in East Sikkim. The project has one powerhouse at the foot of Chuzachen village near the confluence of the Rangpo River and Rongli River near Rongli town in East Sikkim. The project is planned to abstract runoff from both the reservoirs of Rangpo Dam and Rongli Dam through headrace tunnels taking off from each reservoir, and then these tunnels join together to form a single tunnel downstream for a collective water conductor system.

Two independent one-dimensional physically-based numerical models have been developed for the Rangpo River and Rongli River using the well-recognized software, HEC-RAS. The Rangpo Dam and Rongli Dam have been included as inline structures in the respective models. The modelling criteria have been set up and the conventions have been applied to develop the models. The dam-break modelling has been carried out for both dams for various scenarios to analyze the consequences of the dam-break events. The resulting flood hydrographs from each model have been observed and analyzed. The impact of the flood downstream due to the dam-break in terms of flood extent has been displayed on flood inundation maps.

1.1.1. Salient features

The ray diagram of the rivers with the schematic sketch of general layout of Chuzachen HEP has been displayed below:

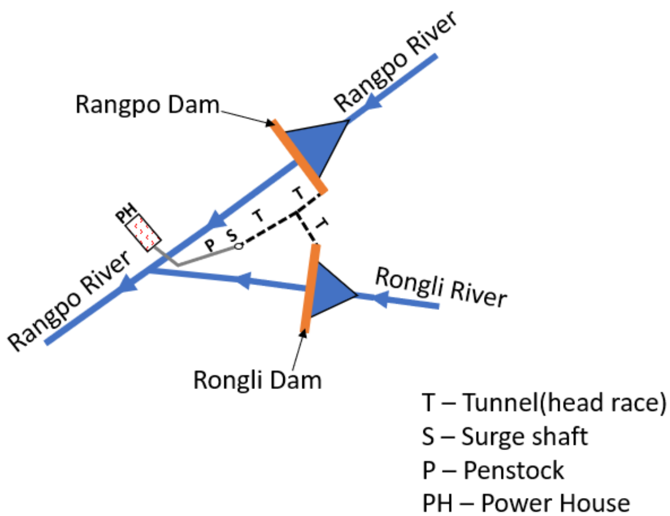

Figure 5. Ray diagram showing Rangpo River and Rongli River

The salient features of the project have been summarized in the following tables:

Table 1. Features of Rangpo Dam and Rongli Dam

Particulars	Rangpo Dam	Rongli Dam
Country, State	India, Sikkim	India, Sikkim
Stream	Rangpo River	Rongli River
Latitude	27°14'17.10"N	27°12'13.99"N
Longitude	88°42'35.68"E	88°42'43.91"E

Table 2. Characteristics of Rangpo Dam and Rongli Dam

Particulars	Rangpo Dam		Rongli Dam	
	Value/Type	Unit	Value/Type	Unit
Dam type	Gravity	-	Gravity	-
Dam crest elevation	915.6	m a.s.l.	915.6	m a.s.l.
Stream bed (talweg) level	880.00	m a.s.l.	884.00	m a.s.l.
Dam foundation level (deepest)	866.00	m a.s.l.	873.00	m a.s.l.

Particulars	Rangpo Dam		Rongli Dam	
	Value/Type	Unit	Value/Type	Unit
Dam height from deepest foundation level	48.0	m	41.0	m
Crest length	186	m	113.83	m
Spillway type (incorporated into the dam)	Ungated Ogee crest	-	Ungated Ogee crest	-
Spillway crest elevation	909.20	m a.s.l.	909.20	m a.s.l.
Spillway crest length	28.5	m	28	m
Flip bucket	-	-	-	-
Bottom outlet (incorporated into the dam)	-	-	-	-
Sill elevation	880.2	m a.s.l.	884.20	m a.s.l.
Number of openings	2	-	2	-
Dimension of opening (h x w)	3.00 x 3.50	m	3.00 x 3.50	m
Gate type	Radial	-	Radial	-
Maximum head	32.8	m	29.60	m
Capacity (by exceptional reservoir level), each opening	260	m^3/s	247	m^3/s

Table 3. Characteristics of Rangpo Reservoir and Rongli Reservoir

Particulars	RangpoReservoir		RongliReservoir	
	Value	Unit	Value	Unit
Full reservoir level (FRL)	909	m a.s.l.	909	m a.s.l.
Minimum drawdown level (MDDL)	893	m a.s.l.	893	m a.s.l.
Total storage volume	360	1000 m^3	199	1000 m^3
Live storage volume	305	1000 m^3	184	1000 m^3
Dead storage volume	55.4	1000 m^3	15.6	1000 m^3

2. Modelling theory and brief description of applied software, HEC-RAS

The physical laws which govern the flow of water in a stream or river are expressed mathematically in the form of partial differential equations:

Conservation of mass (continuity) equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q_1=0 \quad (1)$$

Conservation of momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial QV}{\partial x}+gA\left(\frac{\partial h}{\partial x}+S_f-S_O\right)=0 \quad (2)$$

where:

Q	=	discharge,
A	=	total flow area,
q_1	=	lateral inflow per unit length,
x	=	distance along waterway,
t	=	time,
V	=	velocity,
g	=	acceleration due to gravity,
h	=	depth of flow,
S_f	=	frictional slope, and
S_o	=	bed slope.

The software, HEC-RAS developed byUSACE is designed to perform one-dimensional (1D) and two-dimensional (2D) hydraulic computations numerically for a full network of natural and constructed channels. The above equations are in 1D form and are encrypted in the software, HEC-RAS for solving the equations numerically. The HEC-RAS model comprises two major components; steady flow and unsteady flow. In the present study, both the components have been used. The steady component has been used to calibrate the model, whereas the 1D unsteady fully hydrodynamic model component has been used to model the dam-break scenarios.

The flowchart describing the dam-break modelling mechanism has been presented below:

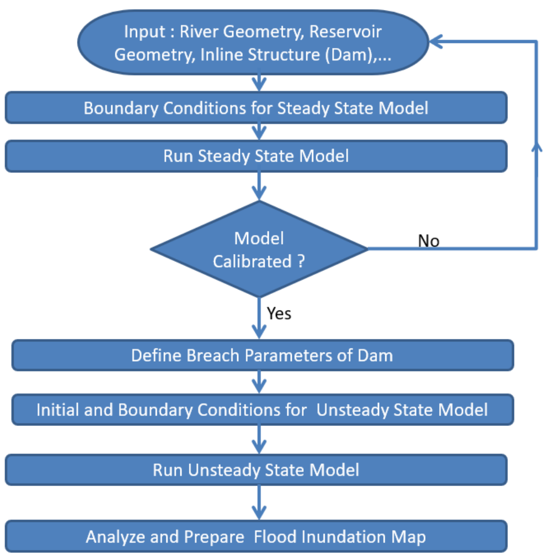

Figure 6. Flowchart of dam-break modelling of Rangpo Dam and Rongli Dam

3. Data organization

The river geometry data and the input data for model set up have been organized as indicated below:

3.1. River geometry

The river cross-sections data to define the geometry of the river have been listed in the table below:

Table 4. Cross-sections of Rangpo River and Rongli River

River Name	Chainage of River Cross-sections (m)	Remarks
Rangpo	0.00	Rangpo Dam at Ch 0.00
Rangpo	0.00 to 13500.00	Cross-section intervals 400m-562.5m
Rongli	0.00	Rongli Dam at Ch 0.00
Rongli	0.00 to 5575.00	Cross-section intervals 475m-600m. Confluence with Rangpo River at Ch. 6600.00

3.2. Storage-area curve of reservoirs and probable maximum flood (PMF) hydrographs.

The capacity area data of Rangpo and Rongli reservoirs and the corresponding PMF hydrographs of the respective catchments at dam locations have been displayed below:

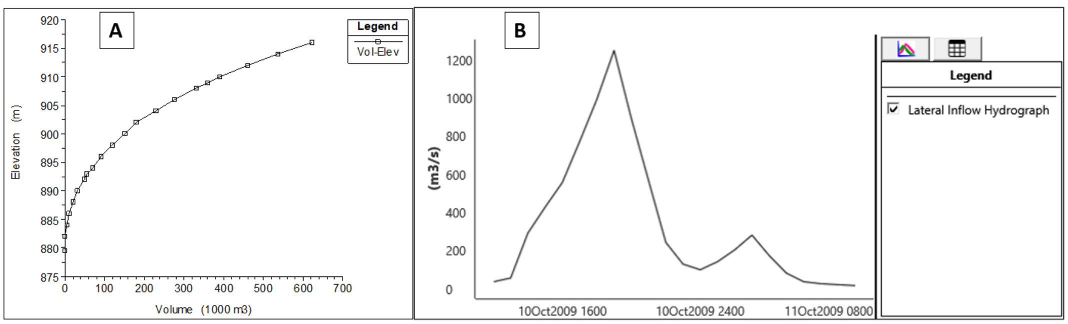

Figure 7. Plot with Box A.Storage-area curve of RangpoReservoir, **Plot with Box B.**PMF Hydrograph of Rangpo Dam catchment

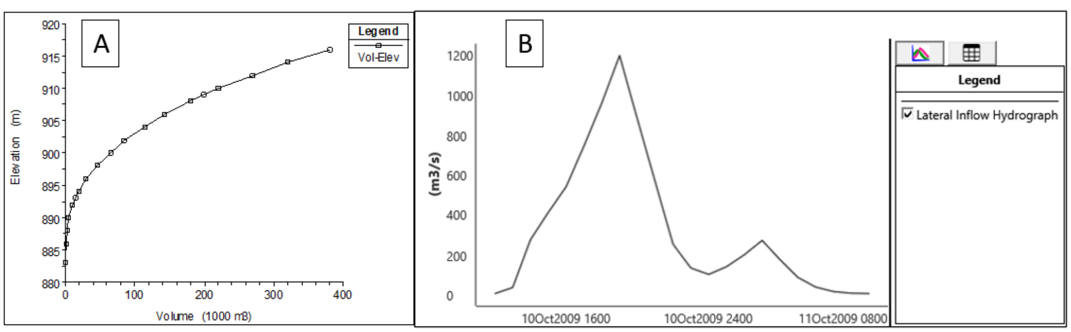

Figure 8. Plot with Box A-Storage-area curve of RongliReservoir, Plot with Box B-PMF Hydrograph of Rongli Dam catchment

4. Dam-break model set-up

The above data have been utilized to set up the physically-based models for Rangpo River and Rongli River with respective inline dam structures using the software HEC-RAS.

4.1. Convention Adopted

The adopted convention to create a dam-break scenario is to simplify the model to represent the river networks. Therefore, two different models of dam-break for the Rangpo Dam and Rongli Dam were set up.

The following assumptions have been made:

1. The dam-break scenarios at both dams are hypothesized at PMF events.
2. The river networks are established independently to represent the entire reach of the river as Rangpo River and Rongli River

3. The confluence network is replaced by introducing additional initial conditions applied at the cross section just downstream of the confluence to represent the flow of the Rongli River to the defined reach of the Rangpo River. Similarly, for the Rongi River model, the flow of the Rangpo River has been set as an initial condition at the cross section just downstream of the confluence.
4. Simultaneous dam-breaks of Rangpo and Rongli are too hypothetical to occur in practice. Hence, avoided.
5. Failure of dams are due to overtopping
6. The sluice gates are closed as it is merely conditional for sediment flushing simi
7. Time series data chosen for hydrographs starts from 10 October 2009 1200 hours to 11 October 2009 0900 hours, which is merely relative to the flood event and universally applied for the simulation.

4.2. Calibration

The Manning's roughness coefficient for different reaches of Rangpo River and Rongli has been initially set as n = 0.04 considering the river beds with boulders and rocks of hilly terrain, and vegetation on the overbanks. (Ref. Open Channel Hydraulics, V.T.Chow). For calibration, a steady state model has been tested by applying the same value of (n) to check the model response against the known water surface elevation values for given discharges downstream near the confluence of Rangpo River and Rongli River near the powerhouse. The models were observed to be approximate, thereby validating the considered roughness value. Hence, the n=0.04 has been applied to the dam-break models.

4.3. Initial and boundary conditions

The project elements that constitute setting up the dam-break model are initial conditions, boundary conditions, and breach parameters. Model is developed for PMF event. The event and the conditions have been tabulated below:

Table 5. Initial and boundary conditions for Rangpo and Rongli dam-break models

Model Name	Flood routing event description	Initial condition			Boundary condition	
		Stage Elevation Upstream (m)	Reservoir Min Elevation (m)	Flow (m^3/s)	Upstream End	Downstream End
Rangpo dam-break	Dam-break at PMF or at Overtopping Stage	909	909	1250	PMF hydrograph, Elevation-Storage Curve	Normal depth
Rongli dam-break	Dam-break at PMF or at Overtopping Stage	909	909	1200	PMF hydrograph, Elevation-Storage Curve	Normal depth

4.4. Critical conditions for Rangpo and Rongli dam-break scenarios

The critical condition for a dam-break study is when the reservoir is at FRL and the design flood hydrograph (PMF) is impinged. Accordingly, in the present study, the reservoir routing has been carried out by impinging the PMFs into the respective reservoirs, assuming that the water levels in reservoirs are at FRL of 909 m. In both reservoirs, the maximum water level reached in the reservoir routing is 917 m, which occurs 7 hours after the application of PMFs. The top levels of both the dams are 915.6 m. It is concluded that when the initial levels of Rangpo Reservoir and Rongli Reservoirs are at FRL, the PMFs can be safely passed as the capacities of the dam spillways are adequate to negotiate the respective PMFs. The critical conditions have been applied to the Rangpo and Rongli dam-break models.

4.5. Breach parameters for Rangpo and Ronglidam-break cases

The breach plan data has been specified at the dam location attached to the cross section just downstream of the reservoir. The spillways of Rangpo dam are represented in HEC-RAS as an inline weir structure and the bottom outlets as sluice gates. Since the inline structure module of HEC-RAS is combined with gates, the opening schedule of gates becomes an additional boundary condition for simulation. Therefore, a time series data with continuous zero opening of sluice gates dictates the closed status of the gates. With the advent of the aforesaid, the breach parameters are defined with assumptions.

The inline dam structure sections of the Rangpo and Rongli dams in the HEC-RAS model have been displayed below.

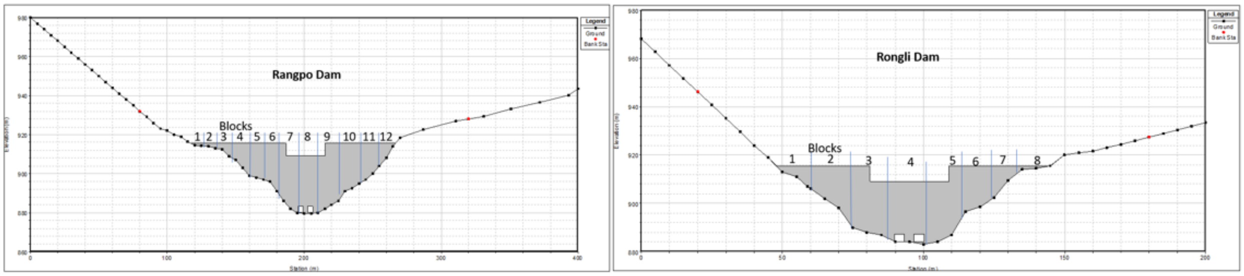

Figure 9. Dam inline structure with indicated blocks in HEC-RAS

As per the U.S. Bureau of Reclamation (1988), for earthfill dams, the ultimate width of a rectangular dam breach shape equals three times the initial water depth in the reservoir measured to the breach bottom elevation assumed to be at the stream bed elevation. This relationship has been used as a guideline in the National Weather Service Simplified Dam-break Model (SMDBRK).

$$B_{avg} = 3H_d \quad (3)$$

where, B_{avg} is the ultimate average breach width and H_d is the water depth in the reservoir initiating the failure.

As per the UK Dam-break Guidelines and U.S. Federal Energy Regulatory Commission (FERC) Guidelines, in the case of concrete gravity dams, the breach width should be taken between 0.2 to 0.5 times the crest length of the dam, and breach development time should be taken about 0.2hour.

On the basis of the above guidelines, the breach parameters are defined with the following rational assumptions:

- the breach side slope of the dam is zero.
- the breach development time is 12 minutes for instantaneous failure.

To model the realistic nature of the breach, two cases of breach width and height are analyzed for both Rangpo and Rongli dams.However, only the selected cases which are comparatively more significant than the others for each dam have been presented. The input breaching parameters for these models are tabulated below.

Table 6. Breach parameters ofRangpo and Rongli dams for different breach cases

Case No	Breach level (m)		Breach width (m)		Breach slope	Breaching time (min)	Dam blocks to be breached
	Initial	Final	Initial	Final			
Rangpo Breach (B-48)	915.6	880.2	48	48	0	12	Block 7,8 and 9 comprising spillways to be broken upto EL 880.2

Case No	Breach level (m)		Breach width (m)		Breach slope	Breaching time (min)	Dam blocks to be breached
	Initial	Final	Initial	Final			
Rongli Breach (B-28)	915.6	890.3	28	28	0	12	Block 3,4 and 5 comprising spillways to be broken upto EL 890.3

5. Results and discussions

5.1. Rangpodam-break

The results of Rangpo dam-break modelling with the above-considered breach height and width have been displayed below.

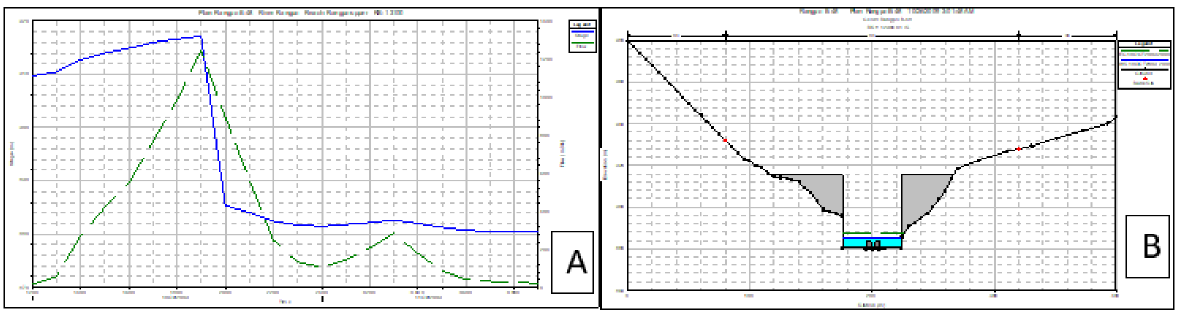

Figure 10. Rangpodam-break**:** Plot with Box A-Inflow and stage hydrographs, Plot with Box B- Rangpo dam breach case (B-48) of considered breach height and width.

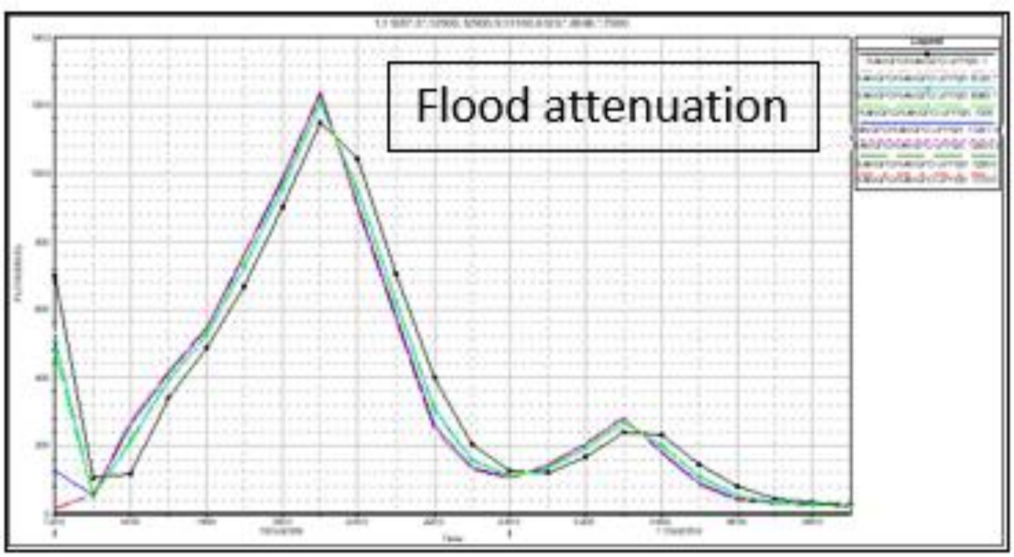

Figure 11. Flood attenuation resulting from Rangpo dam-break model

The inflows and outflow curves as shown in the above figures indicate that the magnitudes of the peaks are not varying high comparatively. The dissonance observed at the start of the run is indicative of the intrusion of flows downstream due to the initial condition of flow at the junction coming from Rongli River. This flow is kept higher to deduce whether the flood wave velocity increases downstream. The sudden increase in flow downstream degrades to the normal depth condition in an interval of 1 hour. The simulation above infers that during a dam-break scenario, the storage behind the dam quickly reduces, thereby having less impact on the normal flow at the downstream end.

5.2. Ronglidam-break

The results of Rongli dam-break modelling with the above-considered breach height and width have been displayed below.

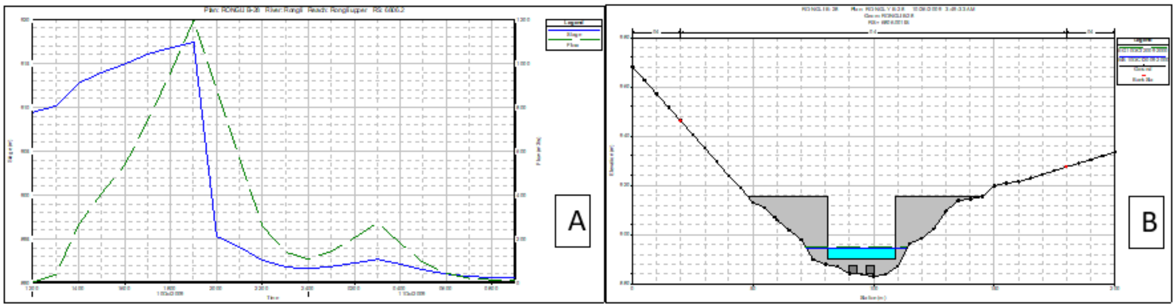

Figure 12. Rongli dam-break: Plot with Box A-Inflow and stage hydrographs, Plot with Box B- Rongli dam breach case (B-28) of considered breach height and width.

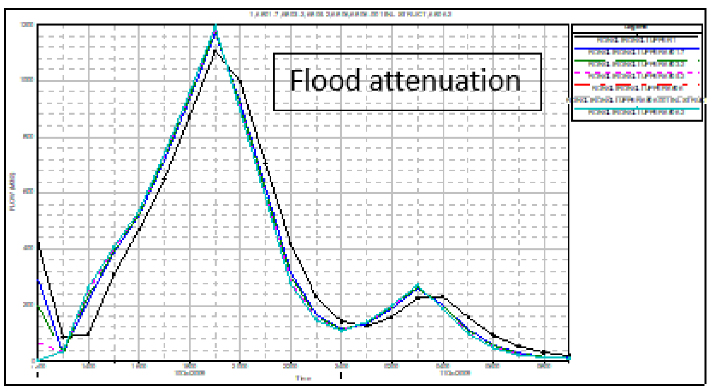

Figure 13. Flood attenuation resulting from Rongli dam-break model

The observation is the same as explained in the case of the Rangpo dam-break above except that the dissonance observed at the start of the run is indicative of flows downstream due to the initial condition of flow at the junction coming from Rangpo River.

6. Flood inundation mapping

From the results of the above dam-break models of Rangpo and Rongli dams, the maximum flood extent lines have been worked out and laid over a contour map to indicate the flood inundation hazard areas. The inundation hazard areas take the shape of a band along the rivers due to the terrain where the river flows through the deep valleys. The inundation hazard areas identify the area that could potentially be affected by inundation in the unlikely event of dam-break of Rangpo Dam and Rongli Dam only and do not reflect any natural hazards, such as flooding from rivers due to cloud bursts, etc. The flood inundation map has been displayed below.

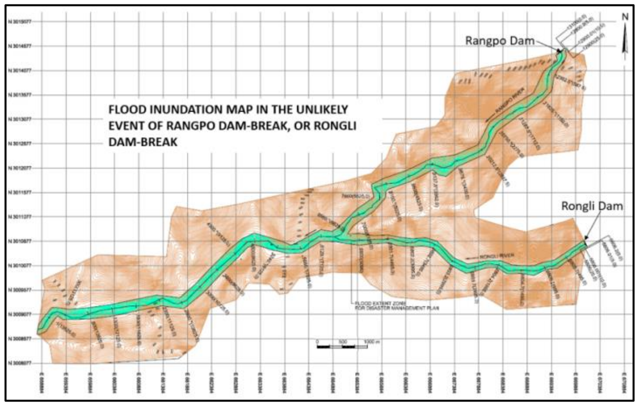

Figure 14. Flood attenuation resulting from Rongli dam-break model

7. Conclusions

1. The dam-break modelling aids in preparing the flood inundation plan, which is vital in resource and catastrophe/hazard management. Based on the flood inundation map ready for the Rangpo River and Rongli River, a flood warning system was highly recommended for installation so that the residents living in the proximity are alarmed in advance for necessary evacuation and for taking safety measures.

2. It would be advisable to place a policy to discourage the inhabitation encroachment towards the Rangpo River and Rongli River that may also be cost-effective for mitigation measures against post-dam-break floods on the downstream reaches of the project.

3. The modeled breach levels and progressions considered in the model are hypothetical and based on various sources, as indicated in the respective sections. Therefore, the study is limited to the said hypothesis. Further research on breach progression is encouraged.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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