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Dam Break Flood Simulation in Natural Floodplain Topography with 1D and 2D Numerical Models

Mimi Das Saikia[1] and Arup Kumar Sarma[2]
Civil Engineering Department, IIT Guwahati
North Guwahati, Guwahati, Assam - 781 039, INDIA
E-mail: [1]minid@iitg.ernet.in/mimidas_saikia@yahoo.com; [2]aks@iitg.ernet.in

ABSTRACT: Floods due to failure of dams induce widespread damages to life and property owing to its high magnitude and unpredictable sudden occurrence. The response time for such flood is quite small compared to natural floods. Simulation models are most useful approach for prior assess of the impacts of the dam break floods. It is required to be simulated to determine the inundated area, flood depth and travel time of the flood waves so that adequate safety measures can be provided. In this study, dam break flood analysis has been carried out through its' application in natural floodplain topography. A hypothetical situation of failure of the proposed dam on the river Dibang, a Himalayan tributary of the river Brahmaputra has been considered. Two different approaches for selecting the 1D computational natural channel have been adopted here. In one approach, the predictions are made by adopting a computational channel, which considers the floodplain downstream of the dam when River Dibang enters the plain (1D-FP). The other approach considers the river channel of Dibang (1D-CH). A 2D model has also been developed and simulation results of 1D models are compared with it. Comparable maximum probable flood depths are predicted by the 2D and the 1D-FP models. The peak depth found to arrive earlier in 1D-FP model i.e., time of peak arrivals are estimated smaller compared to the 2D results. In case of the 1D-CH model, flood parameters are highly overestimated compared to the results of the 2D model. 1D model is computationally highly efficient. The runtime in case of the 2D model is 6413% of that of 1D-FP model.

INTRODUCTION

Considerable efforts have been made in the past to have reasonable understanding of dam break hydraulics. It started with simple cases such as dam failure in rectangular frictionless channel by Ritter's [1]. In the recent decades, there are examples of numerical models for complex channels and floodplains also, e.g., one Dimensional simulation models, Hicks F.E. *et al.* [2], Sanders B.F. [3], Zoppou C. and Roberts S, [4], Macchione F., Viggiani G. [5], and two Dimensional simulation models, Katopodes N.D. [6], Hromadka [7] Akanbi, A.A. *et al.* [8], Zhao D.H. *et al.* [9], Sarma, A.K. [10]. Aureli F. and Mignosa P. [11]. In this study, a hypothetical situation of failure of the proposed dam on the river Dibang, a Himalayan tributary of the river Brahmaputra has been considered. The reservoir extends up to 43,000 m upstream of the dam and the channel meets the river Brahmaputra 63,000 m downstream of the dam. The elevation of the channel bed changes from 545 m to 127 m. Manning's roughness coefficients at different sections are taken as 0.03, 0.032, and 0.035 based on the channel and floodplain characteristic of the river. The important features of Dibang dam are—dam is very high (288 m) and the initial water difference between upstream and downstream is high; subcritical ,mixed and supercritical flows occur in the same section at different time intervals or at different sections in same time interval; there are cross-section alterations (enlargements or narrowings); the flood occupies flood-plain.

To compute the flood under such dam failure conditions, natural channel is generally represented by a simplified channel. Such simplification may lead to erroneous estimation of the important parameters such as maximum probable depth, peak arrival time and inundated area. Therefore, due emphasis should be given in the selection of an appropriate computational channel while simulating a real dam break flood. Two different approaches for selecting the 1D computational natural channel have been applied here for predicting the dam break flood. In one approach, the predictions are made by adopting a computational channel, which considers the whole floodplain downstream of the dam when River Dibang enters the plain (1D-FP). The other approach considers only the original simplified river channel of Dibang (1D-CH). A 2D model has also been developed and simulation results of 1D models are compared with it. Comparable maximum probable flood depths are predicted by the 2D and the 1D-FP models. The peak depth found to arrive earlier in

1D-FP model i.e., time of peak arrivals are estimated smaller compared to the 2D results. The inundated area by 1D-FP model are although found to be more to a little extent but are reasonably comparable. In case of the 1D-CH model flood parameters are highly over-estimated compared to the results of the 2D model.

MATHEMATICAL MODEL

Representation of 1-D Flow

The movement of the wave in the dam-failure situation is governed by gradually varied unsteady flow equation in open channel, i.e., the Saint-Venant [12, 13] equations. It can be represented in matrix form as,

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}=S(U) \qquad \ldots (1)$$

Where:

$$U=\begin{Bmatrix} A \\ Q \end{Bmatrix},\ F(U)=\begin{Bmatrix} Q \\ \dfrac{Q^2}{A}+gI_1 \end{Bmatrix} \text{ and}$$

$$S(U)=\begin{Bmatrix} 0 \\ gA(S_0-S_f)+gI_2 \end{Bmatrix} \qquad \ldots (2)$$

x = direction parallel to the river, t = time, A = cross-sectional flow area, Q = discharge, V = Depth averaged flow velocity, g = acceleration due to gravity; S_0 = bed slope; and S_f = friction slope,

$$I_1=\int_0^{h(x)}[h(x)-\eta]b(x,\eta)d\eta,$$

$$I_2=\int_0^{h(x)}[h(x)-\eta]\left[\frac{\partial b}{\partial x}\right]_{h=h_o}d\eta \qquad \ldots (3)$$

I_1, I_2 = cross-sectional moment integrals; η = integration variable representing the vertical distance to the bottom of the section; b = cross-sectional width at height η; h = water depth above the bottom.

Representation of 2-D Flow

In conservative form as follows,

$$\frac{\partial U}{\partial t}+\frac{\partial E(U)}{\partial x}+\frac{\partial F(U)}{\partial y}=S(U) \qquad \ldots (4)$$

Where:

$$U=\begin{Bmatrix} h \\ V_x h \\ V_y h \end{Bmatrix}\quad E(u)=\begin{Bmatrix} V_x h \\ V^2{}_x h+gh^2/2 \\ V_x V_y h \end{Bmatrix}$$

$$F(u)=\begin{Bmatrix} V_y h \\ V_x V_y h \\ V^2{}_y h+gh^2/2 \end{Bmatrix}\quad S(u)=\begin{Bmatrix} 0 \\ gh(S_{ox}-S_{fx}) \\ gh(S_{oy}-S_{fy}) \end{Bmatrix} \qquad \ldots (5)$$

Where h is the flow depth, V_x and V_y are the flow velocities in x and y directions respectively, g is the acceleration due to gravity S_{0x}, S_{oy} are the bed slopes in x and y directions respectively.

NUMERICAL SCHEME FORMULATION

Modified Predictor Corrector

The well-known MacCormack scheme in a slightly modified form has been used here.

1D Formulation

Predictor step:

$$UP_{ii}=U_i^n-\tau(F^n{}_i-F_{i-1}^n)+\Delta tS_i^n \qquad \ldots (6)$$

Corrector step: It is applied to each node on the basis of the following conditions,

(i) If, $v\le\sqrt{gh_i}$, for sub-critical flow

$$UC_{ii}=U_i^n-\tau[FPi+1-FPi,]-\Delta t(SP_i) \qquad \ldots (7)$$

(ii) If, $v\ge\sqrt{gh_i}$, for supercritical flow

$$UC_i=UP_i \qquad \ldots (8)$$

Finally, the U vector containing value of primitive flow variables in the next time step is calculated as,

$$U_i^{n+1}=\frac{UPi+UCi}{2} \qquad \ldots (9)$$

2D Formulation

Predictor step:

$$UP_{ij}=U_{i,j}^n-\tau(E^n{}_{i,j}-E_{i-1,j}^n)-\tau(F^2{}_{i,j}-F_{i,j-1}{}^2)-\Delta tS_i^n \qquad \ldots (10)$$

Corrector step: It is applied to each node on the basis of the following conditions

(i) If, $\sqrt{Vx^2{}_{i,j}+Vy_{i,j}{}^2}\le\sqrt{\text{gh}_i}$, for sub-critical flow

Corrector:

$$UC_{ij}=U_{i,j}^n-\tau(E^n{}_{i+1,j}-E_{i,j}^n) -\tau(F^2{}_{i,j+1}-F_{i,j}{}^2)-\Delta t(SP_{i,j}{}^n) \qquad \ldots (11)$$

(ii) If $\sqrt{Vx^2_{i,j} + Vy_{i,j}^{\ 2}} \geq \sqrt{gh}_i$, for super-critical flow

Corrector:

$$UC_{i,j} = UP_{i,j} \qquad \text{... (12)}$$

Finally, the U vector containing value of primitive flow variables in the next time step is calculated as,

$$U_{i,j}^{n+1} = \frac{UP_{i,j} + UC_{i,j}}{2} \qquad \text{... (13)}$$

SIMULATION APPLICATION

The hypothetical flood due to the failure of the proposed dam in a Himalayan river Dibang has been considered.

Location of the dam: Country: India, State: Arunachal Pradesh, District: Lower Dibang valley, Dam Site: Latitude: 28°20′, Longitude: 95°46′ 38″ E, Height of the Dam: 288 m.

Hydrology: Catchment area: 11276 km²; Location: Latitude: 28°11′ 50″ N to 29°25′ 59″ N, Longitude: 95°14′ 47″ E to 96°36′ 49″ E, Average annual rainfall: 4405 mm.

Reservoir: Maximum water level: EL 548 m, Full reservoir level: EL 545 m, Length of reservoir: 43 km.

Field Data

The data obtained with the help National Hydro Power Corporation (NHPC) and National Productivity Council (NPC) of INDIA.

FORMULATION OF 1-D MODELS

River Channel 1-D Model (1D-CH)

Non-prismatic parabolic channel has been taken for the computations. To get the parabolic cross-section at a distance downstream the dam, the available terrain data of original river channel section has been taken and the parabolic least square curve for those data is fitted. The ground elevation for a cross-section of that parabolic channel is taken as the elevation of the centre point of the channel-section.

Simplified Floodplain 1-D Model: (1D-FP)

The non-prismatic channel taken in the computations is a parabolic channel. After analyzing the terrain data for the downstream of the dam, it has been observed that when instantaneous failure of the dam will take place, the flow of the huge quantity of water will not be confined only to the original river channel of Dibang but it will spread out to the nearby land areas and also to the different streams flowing parallel to Dibang. Hence the whole terrain downstream is considered for computational channel. To get the parabolic channel cross-section at a point downstream of the dam, the available terrain profile data has been taken and the parabolic least square curve for those data is fitted.

2-D Model

In this section a 2-D numerical model has been developed with an aim to evaluate the relative computing advantages or disadvantages, effort required for preparing input data and the last most important one the comparisons of the computed important flood parameters.

In the model, the flow domain for computations is 106 km × 63 km. The length is (43 km + 63 km = 106 km) along the direction river Dibang and in perpendicular direction it is 63 km.

SIMULATED OUTPUTS BY ALL THE 1-D MODELS AND 2-D MODEL: THEIR COMPARISONS AND ANALYSIS

1-D CH Model and 1-D FP Model

It has been observed that the adoption of the river channel as the computational channel over predicts the maximum flood depth, velocity and under predicts the time of peak arrival at the downstream sections (Figures 1&2)when the river enters the plain compared to the computations by simplified floodplain 1-D model. The overestimation is quite significant after a distance 32 km downstream the dam, with a maximum at 52 km downstream, which is 306.818% higher compared to the computed maximum depth considering the whole terrain downstream of the dam. The time of peak arrival starts increasing remarkably after a distance of 14400 m downstream, when the whole terrain is considered in computation compared to the simplified river channel. It is not logical to consider that the flow will be confined only to its original channel in case of an instantaneous failure of such a high dam. Once the depth of flow crosses the depth of the original river channel, it will start flowing to the nearby floodplain. The proper prediction of the possible extend of inundation downstream of the dam is quite important, as it consists of villages, roads, dense forest, etc. and therefore, for such practical purposes, for proper prediction of the dam break flood, it may be quite realistic and logical to select the computational channel in such a manner that it takes into account the wide floodplain when the river enters the floodplain.

1-D FP Model and 2-D Model

Additional work required to undertake in 2-D modeling are the data preparations for the input. In case of Dibang Dam, 1-D model has 1001 computational points with 1000 intervals of 106 m each whereas the 2-D model has total 6, 01,601 computational points with 1000 × 600 intervals of 106 m each. The computational time is 6413% higher in the 2-D model than that of the 1-D model. The flood levels by the 1-D model are predicted slightly higher than that by the 2-D model in most of the ground point (Figure 3). In the 2-D model the speed of the flood wave is slow. Hence, the time of peak wave arrivals in case of the 2-D model are found to be noticeably overestimated compared to the 1-D model computations (Figure 4).

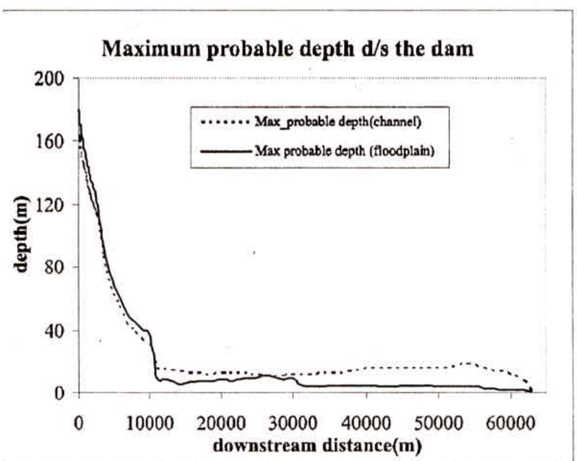

Fig. 1: Comparison of Maximum probable Flood depths

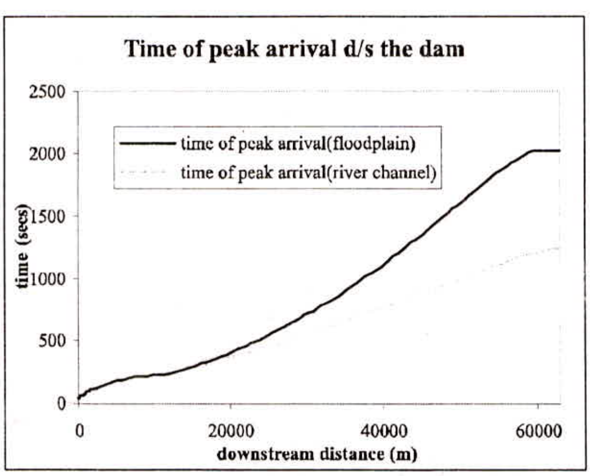

Fig. 2: Comparisons of time of peak arrivals

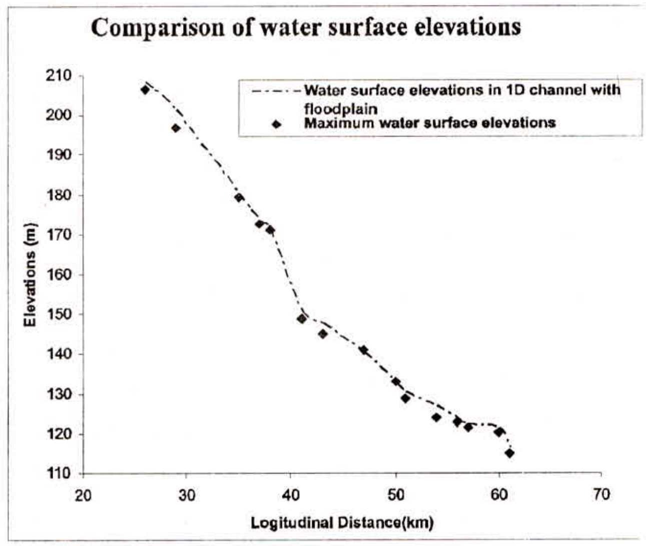

Fig. 3: Comparison of Water Surface Elevations

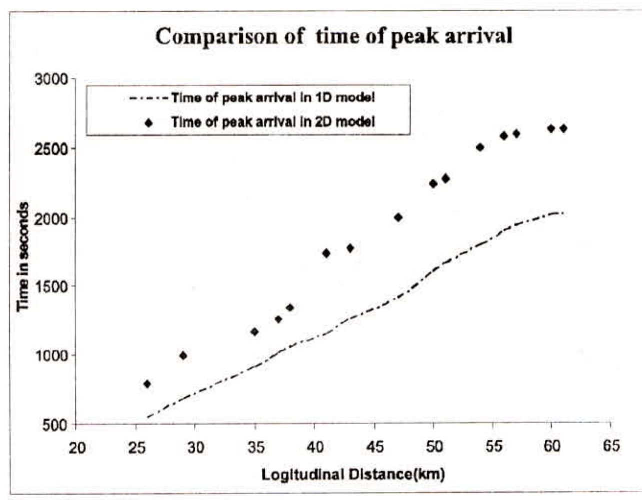

Fig. 4: Comparison of time peak arrival

CONCLUSION

It has been observed that, the 1-D CH model over predicts the maximum flood depth and under predicts the time of peak arrival at the downstream sections when the river enters the plain. The computational time is 6413% higher in the 2-D model than that of the 1-D FP model. The flood levels in the 1-D FP model are predicted higher than that in 2-D .1-D model predicts wave speed faster than that for 2-D model. In case of the 1D-CH model flood parameters are highly over-estimated compared to the results of the 2D model. 1D model is computationally highly efficient. The runtime in case of the 2D model is 6413% of that of 1D-FP model.

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