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Simulation of Dam Break Flood Waves

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Abstract : *One of the aspects of the dam break Emergency Action Plans (EAP) is to describe the anticipated dam failure scenarios and the corresponding arrival times of dam break floods at different locations of interest downstream of a dam alongwith the description of areas that could be inundated. This requires the performance of a dam break analysis as the basis for delineation of possible innundation areas. This paper presents the general principles behind the mathematical models used for dam break analysis, and identifies various available models for dam break analysis. Also a brief description of the well known U.S. National Weather Services DAMBRK model, and its application for the flood wave simulation of the Machhu dam-II failure is presented.*

Introduction

More and more dams have come up or are being constructed with the aim of using the available water resources optimally for developmental purposes or for protecting the lives and properties from the fury of floods. With the assured water resources facility and flood protection provided by the dam, the increase in population and the encouragement for improving the overall economy of the country have led to various developmental activities at the downstream of the dam. This has resulted in the settlement of large population and properties on the flood plain and adjoint areas. However, in the eventuality of a dam failure, the disaster would be catastropic with the flood flow not only occupying the erstwhile floodplain area, but the area adjoining to it. Therefore, it is the responsibility of the organizations involved with the safety of the dams, to prepare dam break Emergency Action Plans (EAP). The purpose of a dam break EAP is to give the authorities of the dam, and any communities downstream from the dam that would be inundated by any portion of a dam break flood wave, the means to identify emergency conditions threatening a dam, expedite effective response actions to prevent failure, and reduce loss of life and property damage should failure occur (Soltys, 1991).

One of the aspects of the EAP is to describe the anticipated dam failure scenarios and the corresponding arrival times of dam break floods at different locations of interest downstream of dam alongwith a description of downstream areas that could be inundated. This requires the performance of dam break analysis as the basis for delineation of possible flood inundation areas.

The dam break analysis involves the following component steps :

i) development or identification of the inflow hydrograph to the reservoir at the time of failure.

ii) routing the inflow hydrograph through the reservoir

iii) development of the failure condition of the dam

iv) calculating the outflow hydrograph from the failed dam, and

v) modelling the movement of the flood wave downstream to determine the magnitude of maximum discharge and maximum water level, and their arrival time, inundated area etc.

Generalised mathematical models have been and continue to be developed for performing dam break analysis. Essentially all present state-of-the-art dam break flood wave models were developed within the last fifteen years. Model development is generally still in a process of continual evolution with updated expanded versions of the models be ng released periodically. A new entrant to the dam break analysis may hestitate to use such models for the simulation of dam break flood waves due to the problem of matching the model assumptions with the real world dam failure scenarios. The serious hesitation is concerned with the failure description of the dam, with the actual failure being far different from that described by the mathematical model. Such a hesitation may be overcome by making suitable assumptions regarding the actual failure mode to suit the failure mode of the model. The other different aspect in dealing with real life dam failure problem is the lack of hydrologic information such as non-availability of inflow flood hydrograph into the reservoir, and the flood hydrograph information downstream of the dam, which could not be measured due to various practical reasons at the time of failure. However, for the purpose of dam break analysis using the model, the inflow hydrograph into the reservoir can be simulated using appropriate rainfall-runoff models. Fortunately in most of the cases one can get the information regarding the maximum water levels reached by a dam break flood wave along the downstream reach by the marks left by the flood wave and by local residents observations. A person well versed with dam break analysis would consider these approximate flow information is more than sufficient for performing dam break analysis, provided all accurate information regarding the structure details of the dam, the cross-section information of downstream channel reach and their roughness are given along with approximate time of development of breach. It has been experienced that the difference between the simulated inflow hydrograph and the actual inflow hydrograph, and the difference between the actual and real failure time and its mode are reflected, only immediately below the dam without giving appreciable discrepancy far away from the dam. Therefore one can confidently use the various available dam break models for simulating hypothetical dam failure scenarios and for the subsequent simulation of dam break flood waves.

This paper presents the general principles behind the mathematical models used for dam break analysis, discusses about the various available models for dam break analysis and their special features. Also a brief description of a case study of dam failure using U.S. National weather services DAMBRK model is presented.

Dam Break Flood Wave Simulation Models

Many types of dam break models exist, ranging from simple computations based on historical dam failure data that can be performed manually to complex models that require computer analysis. The purpose of each model is to predict the characteristics such as peak discharge or stage, volume, and flood wave travel time of a dam break flood. With the availability of improved computational facilities, the empirical models have been replaced by physically based dam break analysis models which simulates the breach on the dam, and routes the flood through the reservoir considering the breach, and subsequently routes the flood hydrograph from the failed dam through the downstream valley. Nevertheless, the empirical models can give first estimate of the expected endangered area, but are, however, inadequate to define these areas, since wave height varies considerably with local narrowing of the valley. Interested readers may refer to Costa (1988) to get to know the details of various empirical models available for dam break analysis.

Simple theoretical estimates of dam break hydrographs originated with Ritter (1892) who used the method of characteristics to obtain a closed form solution for a dam of semi-infinite extent upon a horizontal bed with zero bed resistance. Both experimental and theoretical consideration, however, have shown that the neglect of bed resistance invalidates the Ritter solution as the computed peak discharge tend to be larger than the actual discharges. Ritter's model was improved by various investigators, accounting for bed resistance, however considering the breach to occur instantaneously. Recognising this practical aspect, time dependent breach formation was accounted in dam break models. Most of the available dam break models are based on the general principles outlined below.

General Principles of Dam Break Models

The computation of flood wave resulting from a dam breach basically involves two problems, viz., (1) the determination of outflow hydrograph from the reservoir; and (2) the routing of the flood wave downstream from the breached dam along the river channel and the floodplains. If breach outflow is independent of downstream conditions, or if their effect can be neglected, the reservoir outflow hydrograph is referred to as the free outflow hydrograph. The computation of outflow from the reservoir may be carried out with or without dynamic routing. Each aspect of the above problems will be discussed in some detail below :

Determination of Outflow Hydrograph from the Reservoir :

Depending on the type of dam whether earthern dam or non-earthern dam, two types of flow situations arise within the reservoir at the time of dam failure. In the case of failure of earthern dams, where the breach formation is gradual by the erosion of the embankment material, it may be considered that the water surface within the reservoir is horizontal. This situation implies that the movement of water within the reservoir is insignificant and discharge through the spillway and breach is controlled only by the reservoir storage. Under such circumstances, the reservoir routing may be carried out using hydrologic routing technique. However, when (1) the breach is specified to form almost instantaneously, such as in the case of arch dams masonary dams and concrete dams, so as to produce a negative wave within the reservoir, and/or (2) the reservoir inflow hydrograph is significant enough to produce a positive wave progressing through a reservoir, then the velocity of water within the reservoir may be significant leading to the formation of definite water surface slope. Such a situation demands the use of a dynamic routing technique for simulating the negative and/or positive wave occuring within the reservoir.

With regard to the inflow hydrograph to be used for routing through the reservoir at the time of dam failure, the following thumb rule may be considered. During failures, other than those caused by overtopping, mean flows or small floods, values can be assumed as inflow data, while for overtopping a large natural flood must be assumed. (Petrascheck and Sydler, 1984).

Although the avilable computer programs utilize state-of-the-art hydrograph development and routing techniques, they are dependent on certain inputs regarding the geometric and temporal characteristics of the dam breach. The state-of-the art in estimating these breach characteristics is not as advanced as the computer techniques they are used with, and, therefore, they are limiting factors in dam safety analyses. (MacDonald and Langridge-Monopolis, 1984). Breach forming mechanisms can be classified into two general categories : (1) Breaches formed by the sudden removal of a portion or all of the embankment structure as a result of overstressing forces on the structure, and (2) breaches formed by erosion of the embankment material. The predominant mechanism of breach formation is, to a large extent, dependent on the type of dam.

Examination of the literature on historical failures, indicates that concrete arch and gravity dams breach by a sudden collapse, overturning or sliding away of the structure due to over stresses caused by inadequate design or erossive forces that may result from overtopping of flood flows, earthquakes, and deterioration of the abutment or foundation material. In many cases the entire dam is breached by this mechanism. Examples of such failures are St. Francis dam, Lake Gleno dam and Austin dam in U.S.A. Thus, in the safety analyses of these types of dams, it is prudent and common practice to assume that the breach will develop rapidly, say, of the order of ten minutes, and that the size and shape of the breach will be equal to the entire dam in the case of an arch dam, or a reasonable maximum number of dam sections in the case of a gravity dam. Since not many failure cases of the concrete dams have been reported, it is not surprising to note that serious effort is not made to understand the theoretical aspects of the failure mechanism of the concrete dams. This shortcoming was realised in a recently held symposium during International Commission on large Dams' 57th Executive meeting in Copenhageon and it was stressed that the failure mechanism of the concrete dams should be understood by studying the following main topics (International Water Power and Dam Construction, 1989) :

a) the theory of cracking (fracture mechanics)

b) computational methods available

c) material properties

d) monitoring of cracks

e) validation of theory based on observations; and

f) consequent evaluation of dam safety.

The predominant mechanism of breaching for earthfill dams is by erosion of the embankment material by the flow of water either over or through the dam. Causes that can initiate erosion type breaches include over topping of the embankment by flood flows and seepage or piping through the embankment, foundation or abutments of the dam. In this type of dam failure, the breach size continuously grows as material is removed by outflows from storage and storm water runoff. Thus, the size, shape, and time required for development of the breach is dependent on the erodibility of the embankment material and the characteristics of the flow forming the breach. Breaches of this type can occur fairly rapidly or can take several hours to develop. Also, the size of the breach is often significantly less than the entire dam. Case studies of the failures of the embankment dams indicate that the shape of the breach, in general, is trapezoidal, and the bottom of the breach is at the base of the embankment. MacDonald and Langridge-Monopolis (1984) studied in detail the breaching characteristics of 42 failed dams including the earthern and non-earthern dams. Based on these data they presented various useful relationships for predicting the shape, size and time of breach for the earthern dams.

Flood Wave Simulation Below the Dam

The dam break flood is typically many times larger than the recorded precipitation runoff flood. It has a very short time base, particularly from the beginning of rise to the peak. The rapidly occuring, large magnitude peak discharge results in the dam break flood wave having acceleration components of a far greater significance than those associated with a runoff generated flood wave. As pointed out earlier, measured discharge and stage data are not generally available for model calibration for a dam break flood.

The flow characteristics of a dam break flood wave actually vary in three dimensions. Floodplain irregularities such as abrupt contractions and expansions in valley topography, tributaries, bridges, control structures, and overtopped levees cause accelerations with horizontal and vertical components perpendicular to the flow axis. Water may flow laterally outward from the river channel to fill overbank flood plain storage as the stage rises and then laterally back toward the channel as the stage falls. Three dimensional accelerations can be expected to be particularly significant immediately below the dam. However, multidimensional models are much more complex and difficult to apply than one-dimensional models. For practical applications, the current state-of-the-art of dam break flood wave analysis is one dimensional modelling (Wurbs, 1987) using the St. Venant equations. However, the MIKE-11 of DHI uses two dimensional modelling technique for flow simulation immediately below the dam. Various implicit finite difference schemes are available for the solution of St. Venant equations. Further, most existing mathematical models applicable to dam break analysis assume the river channel to be rigid. In reality, during the passage of dam break waves, the banks and the bed of the valley will be eroded by the flood waves, which affects flood levels.

Commonly used dam break flood wave simulation models

The recognised dam break flood wave simulation models are (Wurbs, 1987) the National weather Service (NWS) Dam-Break Flood Forecasting Model (DAMBRK), U.S. Army Corps of Engineers South Western Division (SWD) Flow Simulation Models (FLOW SIM1 and FLOW SIM2, U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) Flood Hydrograph Package (HEC-1), Soil conservation service (SCS) simplified Dam-Breach Routing Procedure (TR-66), NWS simplified Dam-Break Flood Forecasting Model (SMPDBK), HEC Dimensionless Graphs procedure, MIKE-11 of the Danish Hydraulic Institute has the option for dam break modelling.

DAMBRK, FLOW SIM1, FLOW SIM2 and MIKE-11 are dynamic routing models. FLOW SIM1 and FLOW SIM2 are identical except FLOW SIM1 uses an explicit, and FLOW SIM2 an implicit finite difference solution scheme. The HEC-1 simulates the precipitation - runoff process and routes flood hydrographs using hydrologic methods. The TR-66, SMPDBK and HEC Dimensionless Graphs Procedure are based on precomputed relationships obtained using simplified routing techniques. MIKE-11 of DHI is one of the recently introduced model which simulates two-dimensional flood wave movement immediately below the breached dam, and one-dimensional modelling of flood wave far away from it. It is the only available dam-break model which can account for the effect of the flood wave on the deep erosion of the river bed in the vicinity of the dam and sediment in the downstream areas and adjacent flood plains, Since D.L. Fread's DAMBRK is the most widely known model with various options available for dam break flood wave simulation, it's special features will be briefly discussed herein alongwith its application for a case study.

DAMBRK Model and its Application

The National Weather Services DAMBRK model developed by D.L. Fread (1990) simulates the failure of a dam, computes the resultant outflow hydrograph and simulates movement of the dam break flood wave through the downstream valley. The model is built around three major capabilities which are reservoir routing, breach simulation and one-dimensional river routing using St. Venant equations. However, it does no rainfall-runoff analysis and storm inflow hydrographs to the upstream of reservoir must be developed external to the model. A brief description of these model capabilities are given herein and for detailed description the reader may refer to the user manual of NWS (Fread, 1990).

Reservoir Routing

The reservoir routing may be performed either using storage routing or dynamic routing. DAMBRK utilizes a hydrologic storage routing technique based on the law of conservation of mass and the storage-discharge relationship. However, when the mass of water moves with substantial velocity within the reservoir, dynamic wave routing can be used for reservoir routing.

Breach Simulation

Two types of breaching may be simulated by this model using a linear Mode of breaching in time, or using an erosion based procedure :

(1) An overtopping failure in which the breach is simulated as a rectangular or trapezoidal shaped opening that grows progressively downward from the dam crest with time. Flow through the breach at any instant is calculated using a broad crested weir equation.

(2) A piping failure in which the breach is simulated as a rectangular office that grows with time and is centered at any specified elevation within the dam. Instantaneous flow through the breach is calculated with either orifice or weir equations depending on the relation between pool elevation and the top of the orifice.

The model requires the user to provide the breach descriptions, such as the time to maximum failure, the final elevation of the breach bottom, the side slope of the breach. A schematic diagram showing the breach parameters is given in Fig- 1.

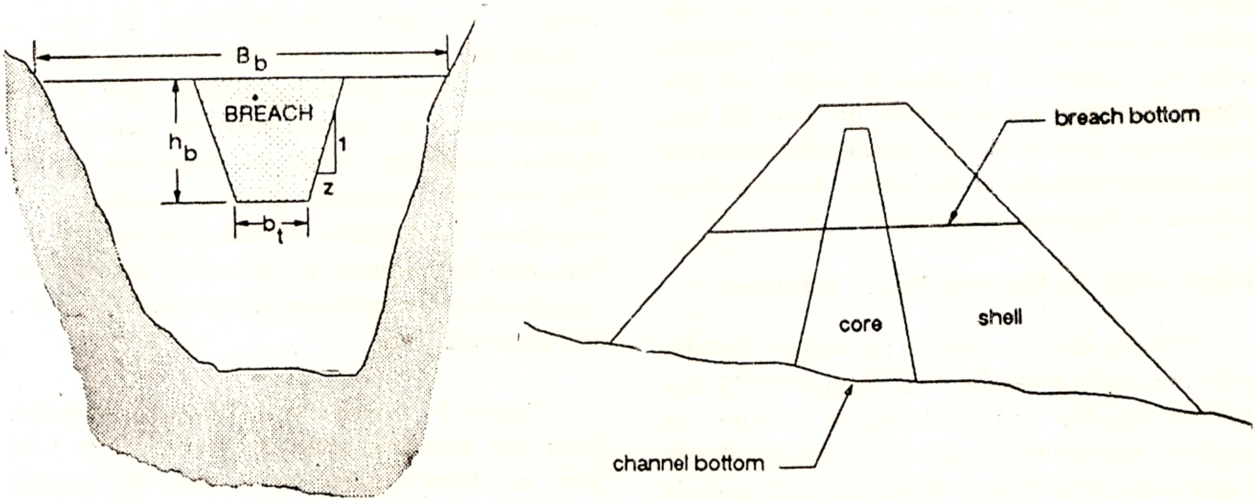

Figure 1. Definition of breach parameter

River Routing

The movement of the dam break flood wave through the downstream river channel is simulated using the complete unsteady flow equations for one dimensional open channel flow defined by St. Venant equations. The finite difference algebraic equations approximating the St. Venant equations are solved by the Newton - Raphson method using weighted four point implicit scheme to evaluate stage and discharge. The initial conditions are given by known steady discharge at the dam, for which water surface elevation at each cross-section are calculated by solving the steady state non-uniform flow equation. The outflow hydrograph from the reservoir is the upstream boundary condition for the channel routing, and the model is capable of dealing with fully supercritical flow or fully subcritical flow or fully subcritical flow or mixed flow, wherein subcritical or supercritical flow exist over specified portion of the channel reach. There is a choice of downstream boundary conditions such as internally calculated loop rating curve, user provided single valued rating curve, user provided time dependent water surface elevation and from overfall. Routing through multiple downstream dams which may or may not fall, and bridges with or without embankment failures can also be handled by the model treating them as internal boundary conditions.

Application to Machhu Dam - II failure

Machhu dam-II which is located on Machhu river in Gujarat failed on 11th August 1979 due to overtopping and subsequent failure of earthern dam portion, leading to the dam break flood wave propagation. More than 2000 people were killed due to this dam failure. A detailed study to simulate the dam break flood wave of Machhu dam - II was carried at the National Institute of Hydrology using DAMBRK model (Perumal and Satish Chandra, 1986).

The data available for the analysis were related to the details of spillway and earthern embankments breach profile, gate opening conditions and the water levels in the reservoir at the time of failure, the cross-section details of the channel reaches and the highest water level marks reached by the flood wave at these sections. The inflow hydrograph was made available for this study, and the analysis was carried out using the options of reservoir storage routing to compute outflow hydrograph from the reservoir, and the subcritical dynamic routing for routing this hydrograph through the downstream reaches. In the absence of flow data at the downstream extreme of the channel, the downstream boundary was assumed as the normal stage-discharge relationship.

At the outset of the analysis, it located to be a difficult problem with regard to the breach description. This was because the actual breach profile, shown in Figure 2, was for different from the profile demanded by the model which can accommodate only rectangular or triangular or trapezoidal shapes of breaches. Therefore, the two breaches one on the left embankment and the other on the right embankment of the dam were combined to form a trapezoidal breach. The variation of model breach flow from the actual breach flow due to the difference in shape, breaches occurred at different locations, effect of roughness on the flow through breaches, effect of contraction - expansion coefficients of the breaches on the flow may be assumed to be small when compared with the magnitude of flow occuring from the breached dam.

Figure 3 shows the outflow hydrograph from the breached dam beginning from 1.30 p m. on 11th August 1979, and the routed hydrographs at cross-sections 5.81, 10.81, 15.81, 20.69 aod 24 63 miles downstream of the dam for a duration approximately upto the respective time to peaks. Figure 4 shows the peak flood elevation profile computed using the model at various cross-sections obtained by interpolating the supplied cross-sections. The observed peak elevations are also shown in the

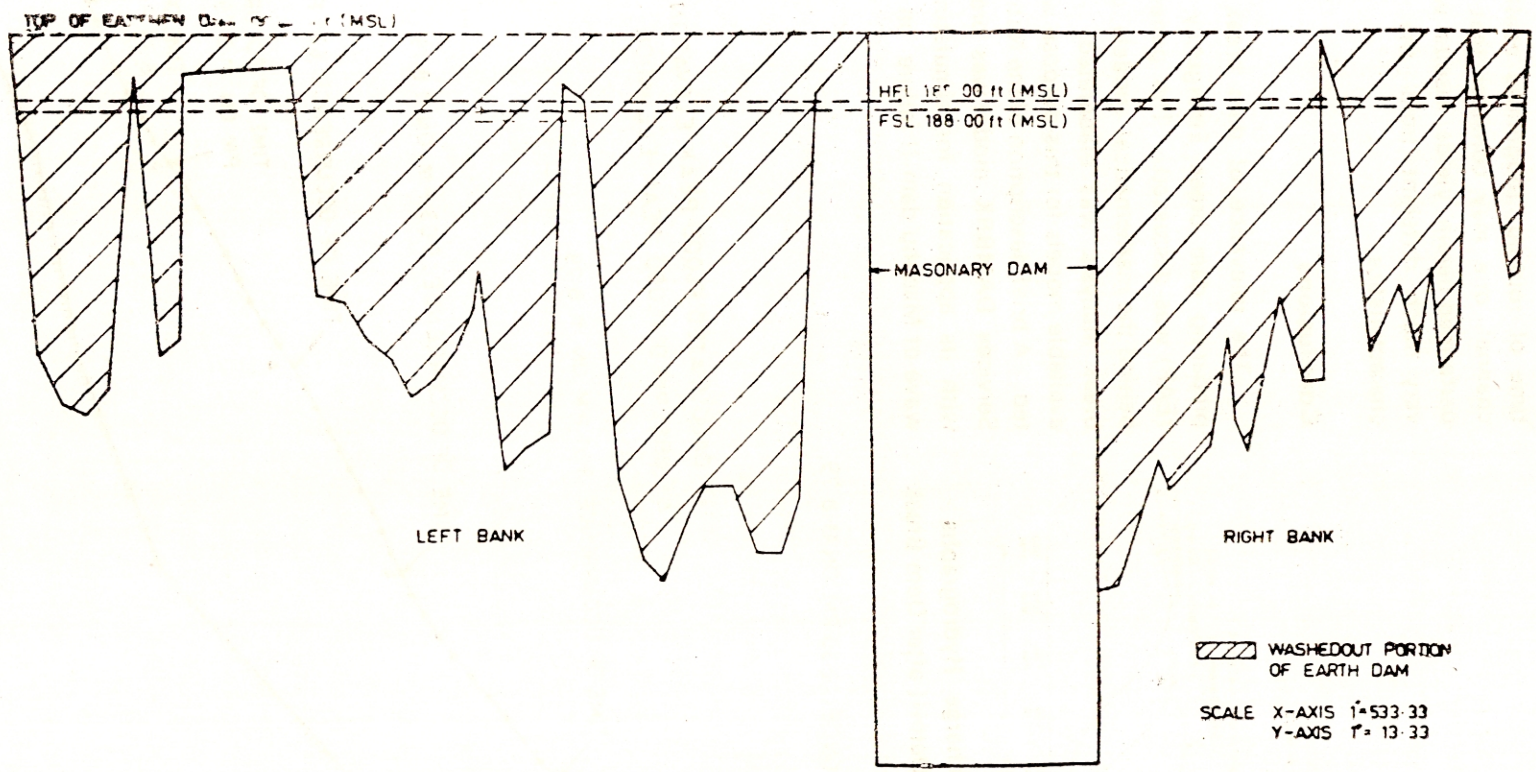

Fig. 2 : Breach Profile of Machhu Dam-II

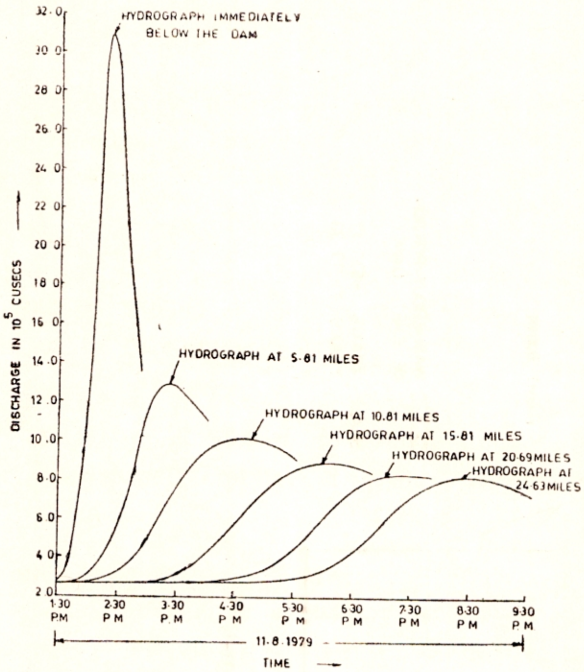

Fig. 3 : Computed Discharge Hydrographs Downstream of Machhu Dam-II after Dam Break

same figure. Considering the uncertainty regarding inflow information into the reservoir, breach time, initial flow in the channel at the time of routing, roughness coefficient of the channel, one may consider that the analysis performed herein yields results which are not very much different from the actual flood characteristics.

Conclusions

The relevance of dam break analysis for preparing dam break Emergency Action Plans (EAP) was discussed. The general principles behind the mathematical models used for dam break analysis was elaborated. The various available models for this purpose was enumerated. A brief description of the National Weather Services DAMBRK model was presented along with its application for simulating the flood wave of Machhu dam-II failure on 11th August

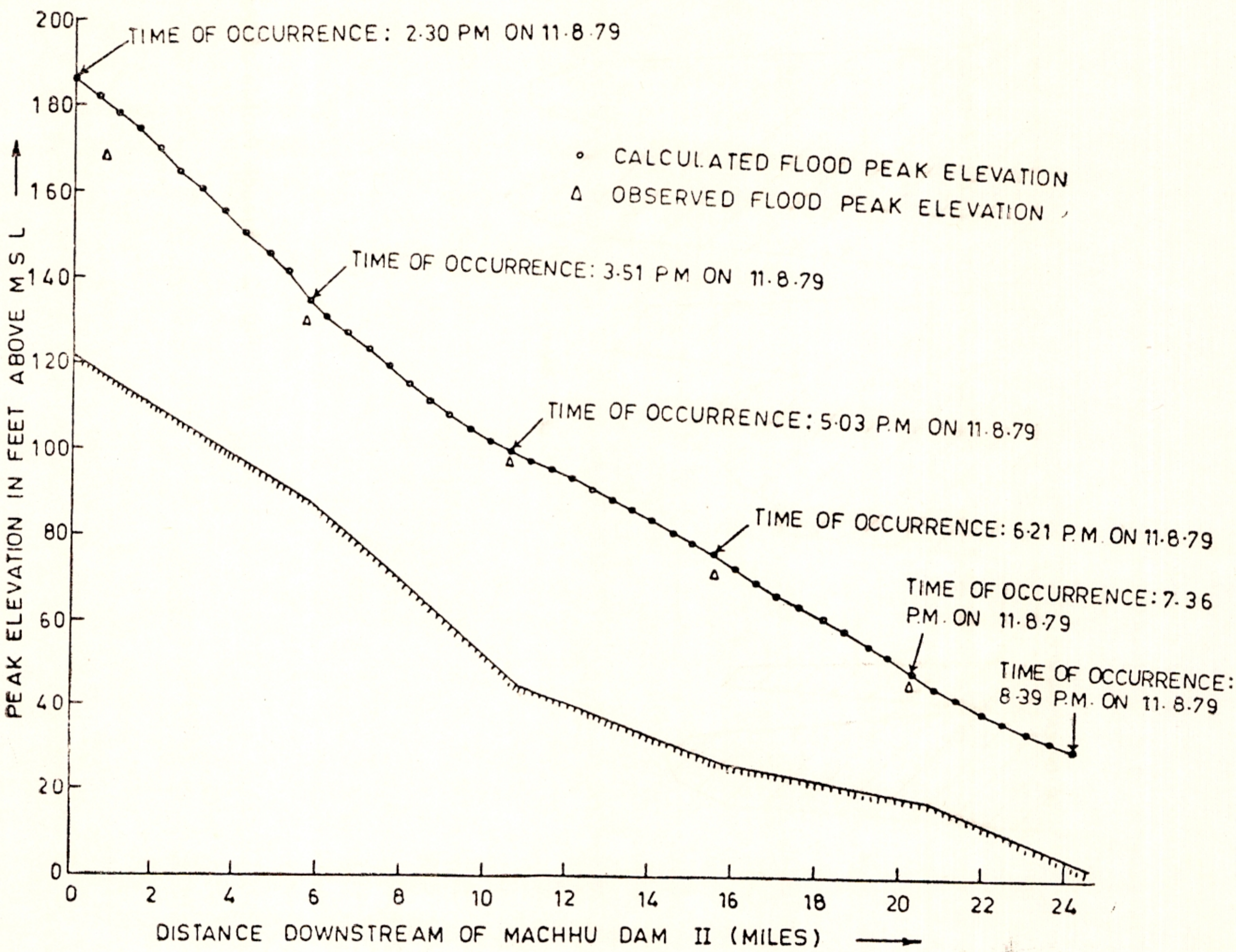

Fig. 4 : Peak Food Elevation Profile from Machhu Dam-II Failure

1979 which killed more than 2000 people. The conclusion one can arrive based on this case study is that the dam break models may be used without any hesitation for analysing hypothetical dam failures for preparing dam break EAP, eventhough the breach formation in reality may not occur in a mode demanded by the model,

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