Dam Failure Modes & Consequences Emergency Action Plans (EAPs) for Dams

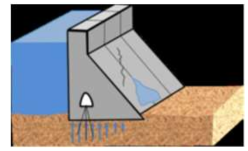
Prof. D. Nagesh Kumar
Dept. of Civil Engg.
Indian Institute of Science
Bangalore – 560 012, India

URL: http://www.civil.iisc.ac.in/~nagesh

1

Types of Dams

- Dams may be classified by the type of construction material used, being listed as either a masonry/concrete or an embankment dam or a Composite Dam
- **Concrete dams** include arch, buttress, concrete gravity, multi-arch, and roller-compacted concrete (RCC) dams
- Other types of concrete/ masonry dams may include hollow gravity and buttress dams.

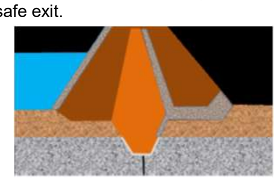


Source: Guidelines for Mapping Flood Risks Associated with Dams, DRIP, Dam Safety Rehabilitation Directorate, Central Water Commission, Government of India, New Delhi, Jan 2018

2

Types of Dams – Contd ..

- **Embankment dams** are made of earthen materials and may be filled with rock, clay, or other materials resistant to erosion.
- Central core made of impervious material helps to cut down seepage losses from the dam, while the permeable filter downstream captures the seeping water and provides it a safe exit.
- A cut-off wall under the dam increases the length of the seepage path and reduces the chances of piping through the foundation



3

Dam Failure - Causes

- Flood or dam overtopping
- Piping or seepage
- Structural failure
- Failure of its spillway gate
- Earthquake
- Poor design/ construction

4

Dam Failure - Modes

- Hydrologic Failure Mode
- Geologic Failure Modes
- Piping Failure/ Internal Erosion
- Structural Failure Modes
- Seismic Failure Modes

5

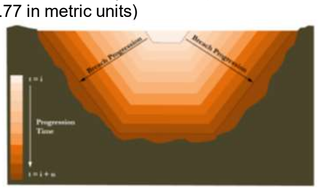
Hydrologic Failure Mode

- Hydrologic dam failures are induced by extreme rainfall or snowmelt events that may cause natural floods of variable magnitude
- Main causes of hydrologic dam failure include overtopping, structural overstressing, and surface erosion due to high-velocity flow and wave action
- Overtopping because of flooding is the most common failure mode for embankment dams
- Overtopping usually results from a design inadequacy of the dam/ spillway system and reservoir storage capacity to handle the flood event
- For embankment dams, the failure begins at a downstream location, with head cutting progressing upwards gradually

6

Hydrologic Failure Mode – Contd ..

- As it reaches the dam top, the width of the dam crest is eroded fast, before the reduction in height starts taking place
- Earthen dam without a core behaves mostly like a sharp crested weir (discharge coefficient C = 1.77 in metric units)
- The opening created by erosion expands gradually, almost in the shape of a trapezoid



Breach progression in case of an overtopping failure

7

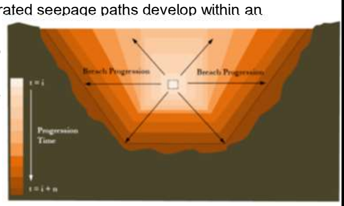
Geologic Failure Modes

- Geologic failure modes may include piping and internal erosion as well as slope instability and hydraulic fracturing.
- For embankment dams, geologic failures may be caused by continuous seepage of water stored in the reservoir
- Geologic failure may also be the result of the inadequate geotechnical design of the embankment and foundation, inadequate seepage controls, or increased load situations such as the rapid increase of water level or drawdown of water level due to a flood, landslide, earthquake, or wave action

8

Piping Failure

- Piping failures occur in earthen dams only
- Piping occurs when concentrated seepage paths develop within an embankment dam
- Seepage slowly continues to erode the dam embankment or foundation, leaving behind large voids in the soil
- Piping begins near the downstream toe of the dam and works its way toward the reservoir upstream



Breach progression in case of a piping failure

9

Internal Erosion

- Internal erosion is different from piping as it originates internally, while piping originates externally
- Internal erosion occurs where two adjacent zones meet within the embankment, or at the zone of contact between the embankment and foundation
- In other words, it is the transportation of the finer grained soil portion of a well-graded soil by water due to either mechanical or chemical action
- Internal erosion near the dam foundation may be a result of poor foundation treatment

10

Structural Failure Modes

- Structural failures occur when there is a failure of a critical dam component
- Structural failure of the main embankment of a dam may be related to internal piping; or due to overloading during a flood event, a critical component of the dam may fail
- Structural failures of concrete dams may occur with the loss of the entire concrete dam structure or loss of particular monolith sections only

11

Seismic Failure Modes

- Seismic failures are related either to ground movement or to liquefaction.
- Ground movements may result in a shift, settlement, or cracking of a dam into an undesirable configuration, which prevents the dam from performing as designed
- For embankment dams, two failure scenarios are envisaged: liquefaction and seismic induced piping
  - Liquefaction may occur when soils are loaded causing the soil to be transformed from a solid into a liquefied state – results in slumping
  - Seismic-induced piping may occur through the internal cracks developed due to ground motions of an earthquake
- Failure mechanisms due to seismic activities may include slope instability, permanent deformations, fissures or cracking, differential settlement, breaking of principal spillway and liquefaction

12

Human-Influenced Failure Modes

- Human-influenced dam failure may be related to improper design or maintenance, mis-operation (sudden/uncontrolled/ unscheduled/ accidental opening of gates), or acts of terrorism.

13 D Nagesh Kumar, IISc Dam Failures & EAPs

13

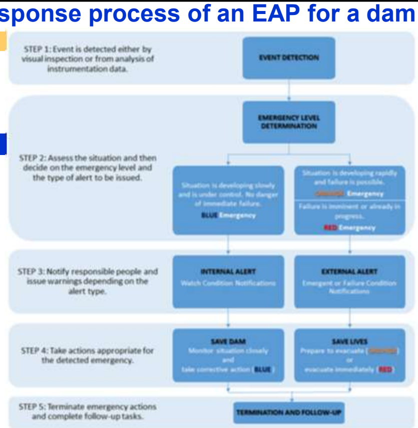
Emergency Action Plans (EAPs) for Dams

Source: Guidelines for Developing Emergency Action Plans for Dams, DRIP, Dam Safety Rehabilitation Directorate, Central Water Commission, Government of India, New Delhi, Feb 2016

14 D Nagesh Kumar, IISc Dam Failures & EAPs

14

Five-step response process of an EAP for a dam



15 D Nagesh Kumar, IISc Dam Failures & EAPs

15

Event Detection – Useful Information

- Measures for detecting existing or potential failures
- Operating information, such as normal and abnormal reservoir level data
- Description of monitoring equipment, such as water level sensors and early warning systems
- Monitoring and instrumentation plans
- Inspection procedures
- Process for analyzing and confirming

16 D Nagesh Kumar, IISc Dam Failures & EAPs

16

BLUE Emergency Level - Examples

- Adverse meteorological conditions
- Detection of anomalies in
  - Dam structural elements
  - Dam operational elements
  - Dam observation system
- Existence of foundation problem

17 D Nagesh Kumar, IISc Dam Failures & EAPs

17

ORANGE Emergency Level - Examples

- Rising reservoir levels that are approaching the top of the non-overflow section of the dam
- Transverse cracking of an embankment
- A verified bomb threat

18 D Nagesh Kumar, IISc Dam Failures & EAPs

18

RED Emergency Level - Examples

- Imminent dam failure because of flood waters overtopping the dam crest, or because of large flows appearing from channels (piping) eroded through the embankment.
- Dam failure in progress

19

19

Description of Emergency Alert Levels

Type of alert	Emergency level	Situation	Actions to be taken
INTERNAL ALERT (Watch Condition Notifications)	BLUE	Existence of anomalies or events that are either harmless or might compromise to some degree the structural or operational safety of the dam or the dam observation system. The situation is stable or is developing extremely slowly. Existing problems must lead to the belief that no serious consequences are expected downstream of the dam, and impacts (if any) will be small and confining to immediate downstream areas of the dam. Events leading to such a slowly developing situation include the following: 1. Existence of adverse meteorological conditions; 2. Existence of minor foundation problems	1. Issue Watch Condition notifications with a BLUE emergency level alert. 2. Monitor situation closely. 3. Take corrective measures to solve the problem.
EXTERNAL ALERT (Failure Condition Notifications)	ORANGE	Situations with a high probability of dam failure, with the belief that it might not be possible to control the situation and might cause serious consequences downstream of the dam. Events leading to such a rapidly developing situation include the following: 1. Detection of severe anomalies in dam structural elements, or in dam operational elements 2. Existence of severe foundation problems 3. Occurrence of extremely large floods. Under these conditions the dam owner or operator might call for assistance from outside agencies. "Some amount of time" will be available for analysis, decisions, and mitigation before off-site impact will probably occur.	1. Issue Failure Condition notifications with an ORANGE emergency level alert. 2. Take corrective emergency measures to solve the problem. 3. Warning – Population downstream of the dam to prepare for evacuation.
	RED	Situation of inevitable catastrophe described as follows: 1. Imminent dam failure because of flood waters overtopping the dam crest, or appearance of large flows through channels (piping) eroded through the embankment. 2. Dam failure in progress. No time will be available for analysis, decisions, and mitigation to be made before downstream impacts occur.	1. Issue Failure Condition notifications with a RED emergency level alert. 2. Issue the most severe evacuation warning. Focus on evacuating first those most at risk. 3. Warning – Immediate evacuation.

20

20

Tiered approach to dam breach inundation mapping for use in EAPs

Tier Level	Applications	Breach Parameter Prediction	Peak Breach Discharge Prediction	Downstream Routing of Breach Outflow Hydrograph	Downstream Risk Evaluation
Tier 1 – Basic level screening and simple analysis using low resolution terrain data (e.g., SRTM, ASTER, or ALOS)	• First level screening for significant or high hazard dams • Low hazard potential dams	Empirical formulae	Empirical formulae if inflow design flood hydrograph is not available, otherwise unsteady flow routing through modelled reach	Geo-Dam-BREACH, SMPDBK, HEC-HMS, or other simplified approaches	Peak discharge, water surface elevation, and flood wave travel time
Tier 2 – Intermediate level of analysis using medium resolution terrain data (e.g., 10 m INTERMAP or Lidar	• Large significant hazard dams • All high hazard dams	Empirical formulae	Unsteady flow routing through modelled breach	HEC-HMS, HEC-RAS, MIKE-11 or similar one dimensional (1D) unsteady flow numerical models	Peak discharge, water surface elevation, flood wave travel time, and approximate PAR assessment
Tier 3 – Advanced level of analysis using high resolution Lidar terrain data	• Significant hazard dams with complex downstream flooding • High hazard dams with large population at risk (PAR)	Empirical equations, WinDAM-B, or causal embankment erosion numerical models (one or two dimensional)	Unsteady flow routing through modelled breach	One or two dimensional (2D) unsteady flow numerical models	Peak discharge, water surface elevation, flood wave travel time, and detailed PAR assessment

21

21

Thank You

22

22