Experimental Investigation and Numerical Modelling of Dyke Failure by Overtopping

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Motivation

Levee failure by Hurricane Katrina, August 2005

Levee breach on the Mississippi River, June 2008

- Dikes and dams are essential infrastructures for water resources management and also for flood control
- Inundation by dam and dikes breaches results in loss of lives and severe property and environmental damage
- Reliable simulation tools are needed for land-use management and for civil protection safety plans
- Breach formation mechanisms are not completely described

Recent studies: geotechnical failure occurs in discrete events but the breach discharge hydrograph is continuum

Most laboratory tests are performed on facilities with no longitudinal flow

GOALS

1. Study the influence of longitudinal flow along the dike in the breach development
2. Achieve a more accurate description of the hydraulic and geotechnical:
   - relation between breach enlargement and the increase in the breach outflow
3. Develop an integrated mathematical model for earth embankment breaching due to overtopping:
   - incorporation of a geotechnical solver in the hydraulic model

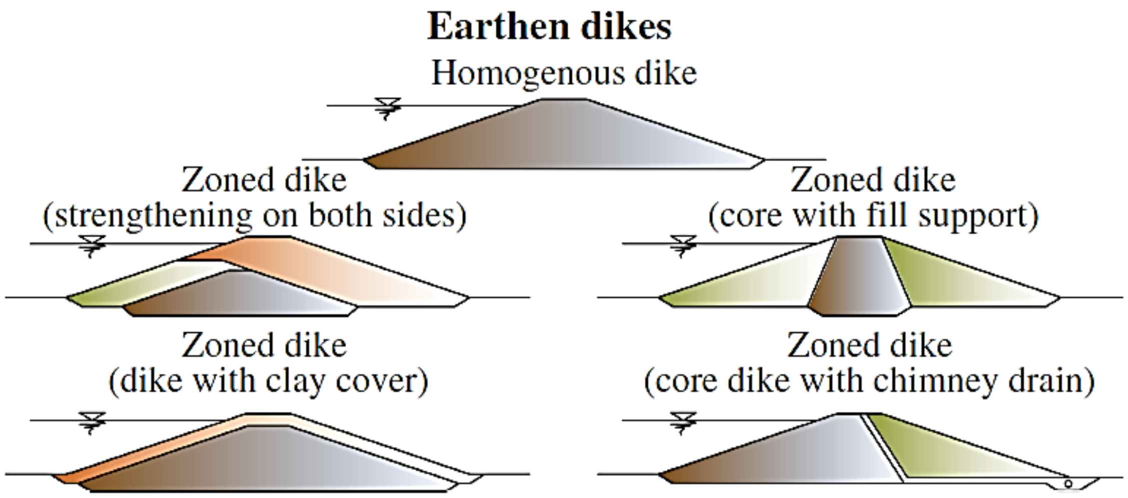
Obtain detailed information on the geotechnical and hydrodynamic phenomena:

Characterization of the occurrence of sudden mass detachments and local flow pattern

Breach in Canal del Dique in Columbia, December 2010

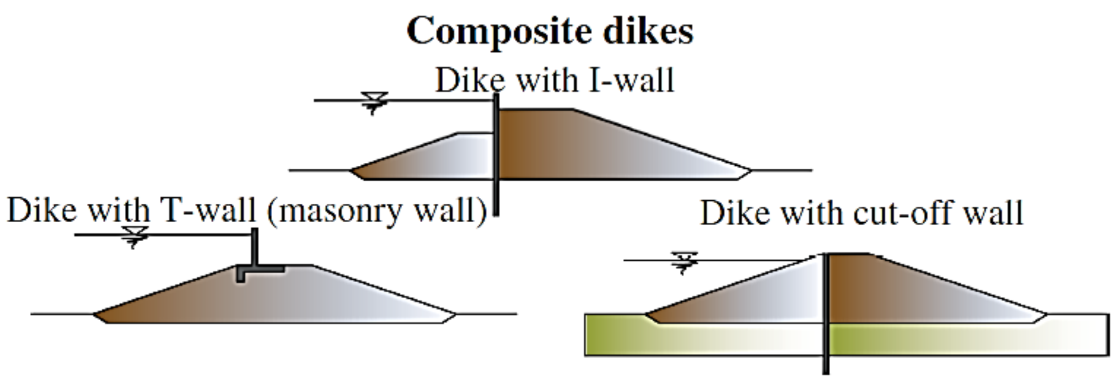
Breach in an Elbe River dike east of Berlin, June 2013

EMBANKMENT DIKES



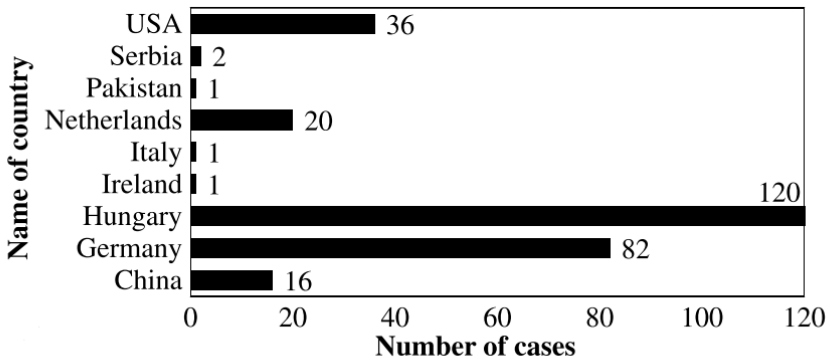
Constructed of granular or clay soils, with the materials satisfying the requirements of water retention and stability

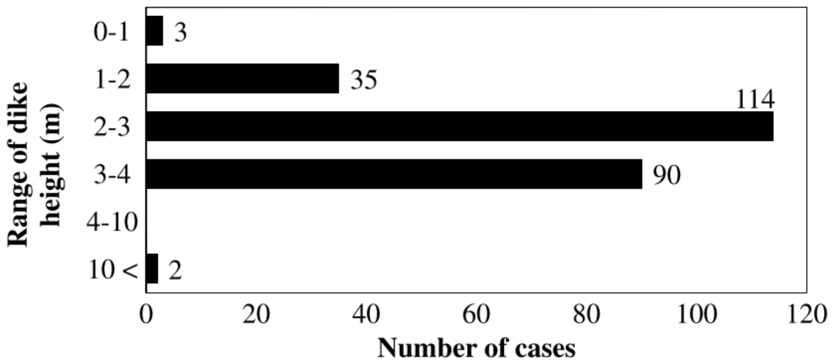
Include additional superstructures or embedded structures (e.g. masonry wall, cut-off wall, spillway and discharge pipes)



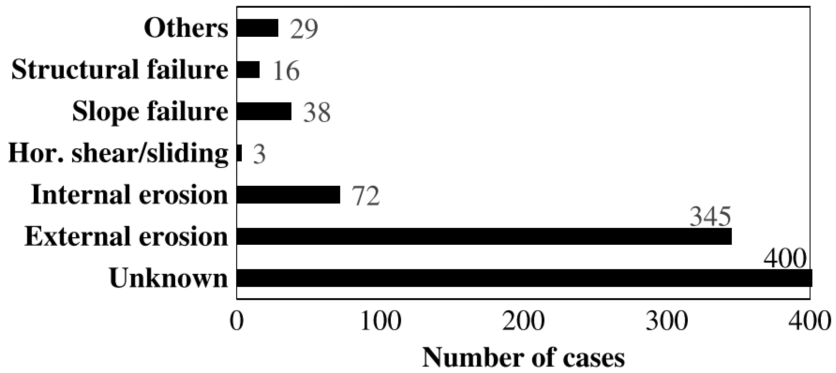
STATISTICS OF DIKE FAILURES

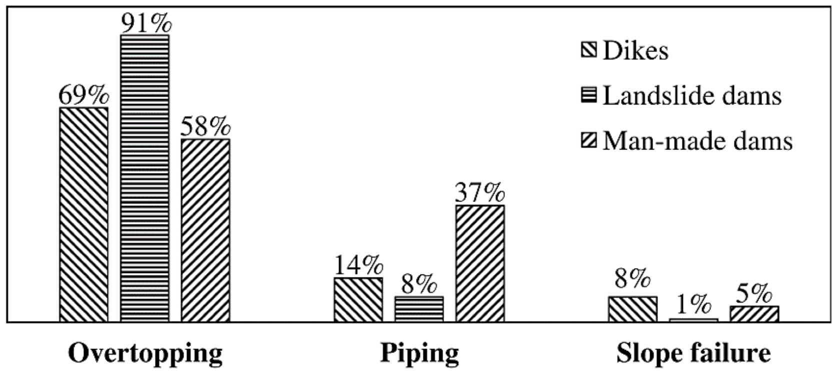
Locations and heights





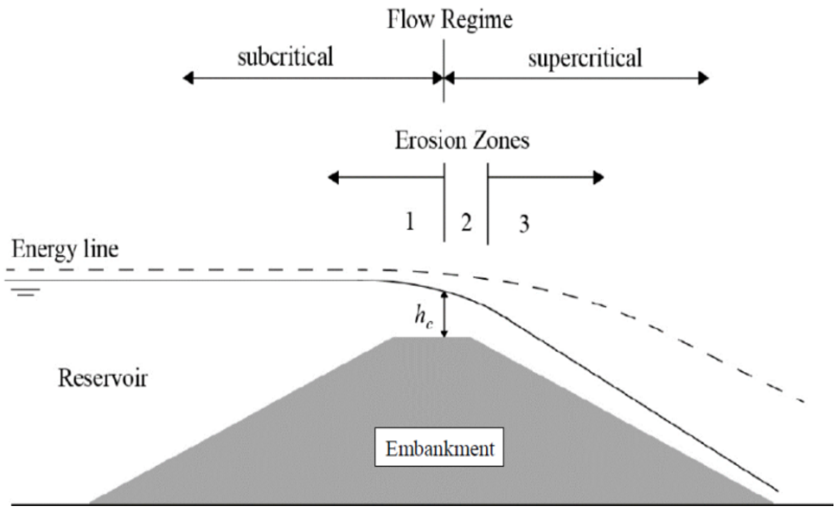
Failure mechanisms





CHARACTERISTICS OF OVERTOPPING FAILURE

Flow regimes and erosion zones



Breach extent

- Duration of overtopping
- Maximum flow velocity
- Tailwater conditions
- Embankment configuration
- Types of material
- Fill densities
- Discontinuities (berms, roads, outlets, cracks or voids in the slope)

Breach development phases

Initiation:

The embankment has not yet failed, and outflow is slight

The embankment collapse may be prevented, if the overtopping flow is stopped

Development:

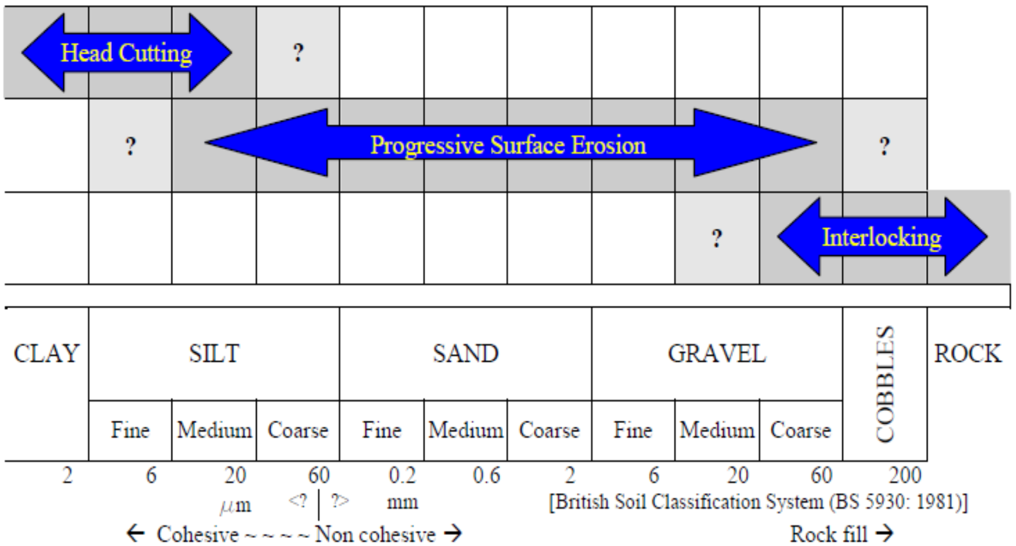
Outflow and erosion are rapidly increasing

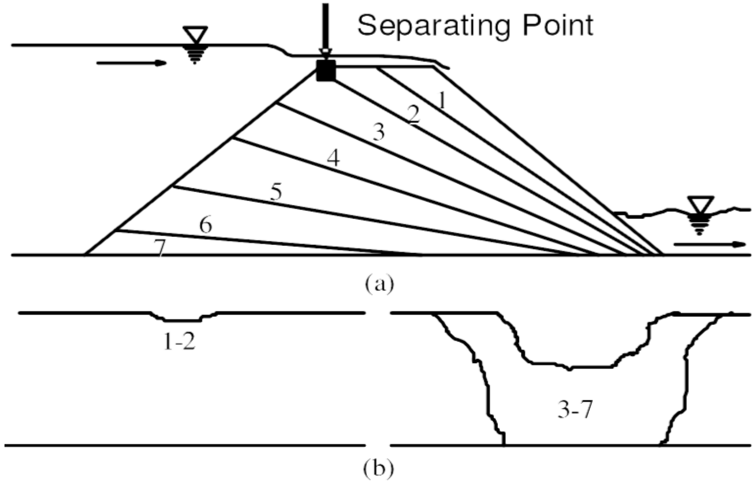
It is unlikely that the outflow and the failure can be stopped

GRANULAR VS CLAY EMBANKMENTS

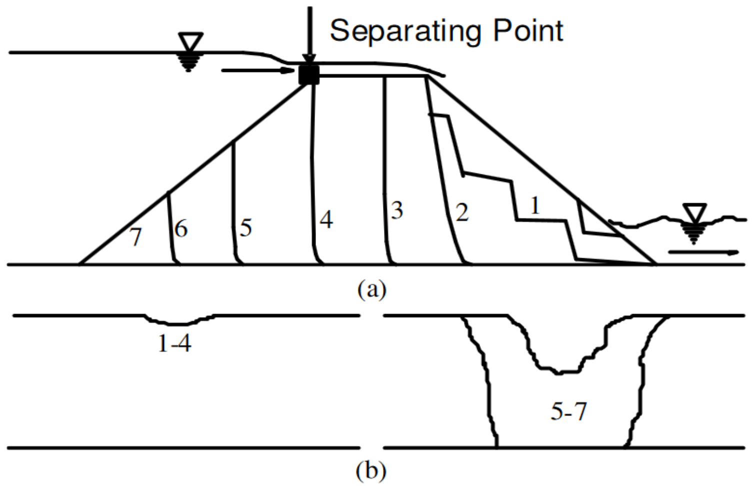
Granular (sand / non-cohesive) embankments:
Progressive surface erosion

Clay (cohesive) embankments:
Headcuts that deepen and enlarge over time, migrating upstream through the embankment



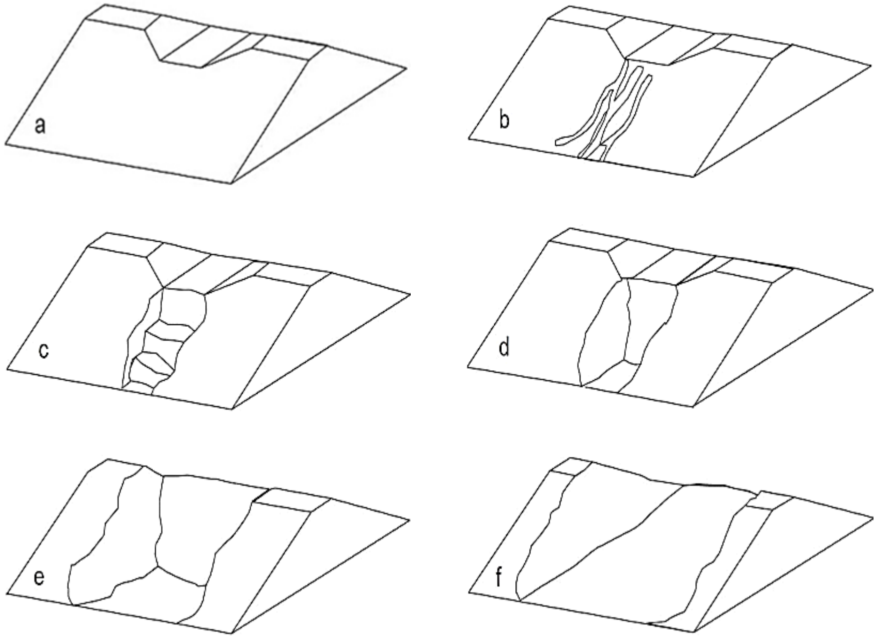


Granular embankments

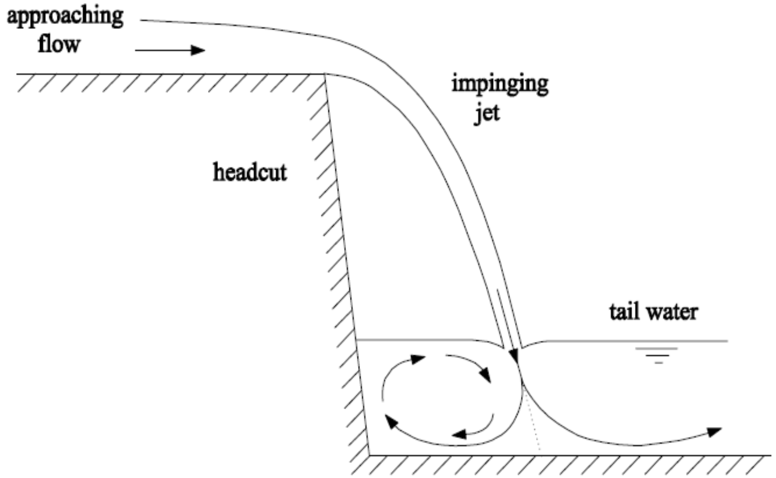


Clay embankments

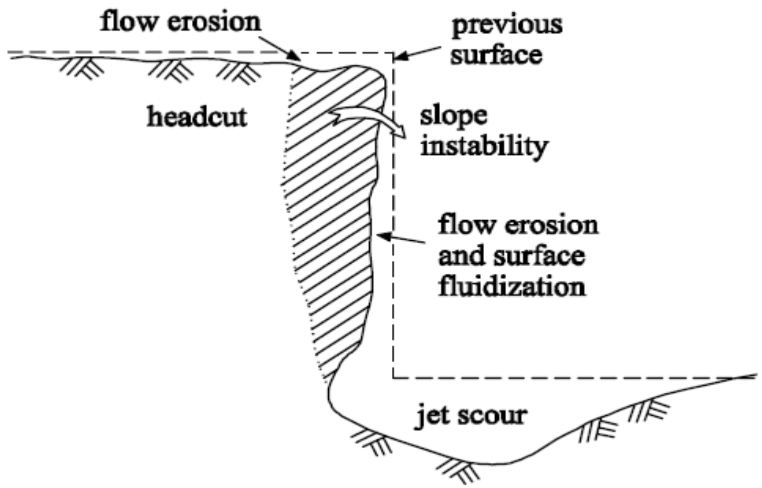
CLAY EMBANKMENTS



Breach initiation: a-d / Breach development: e-f

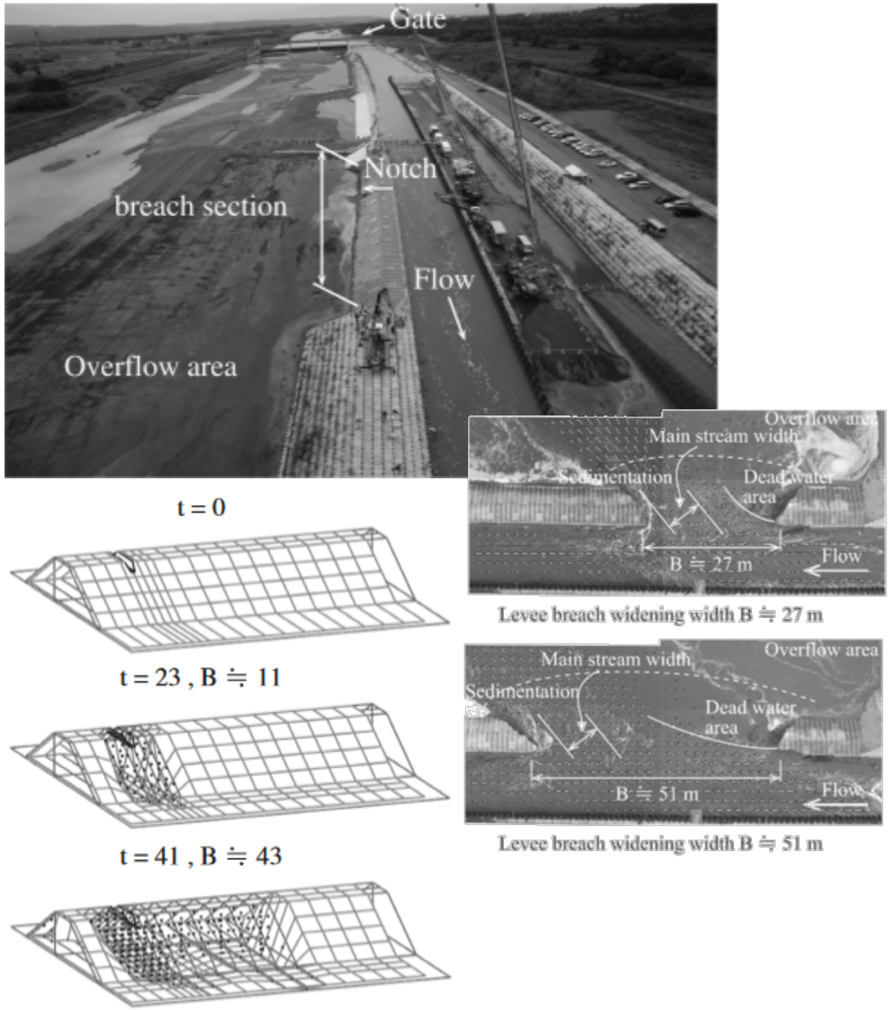


Headcut

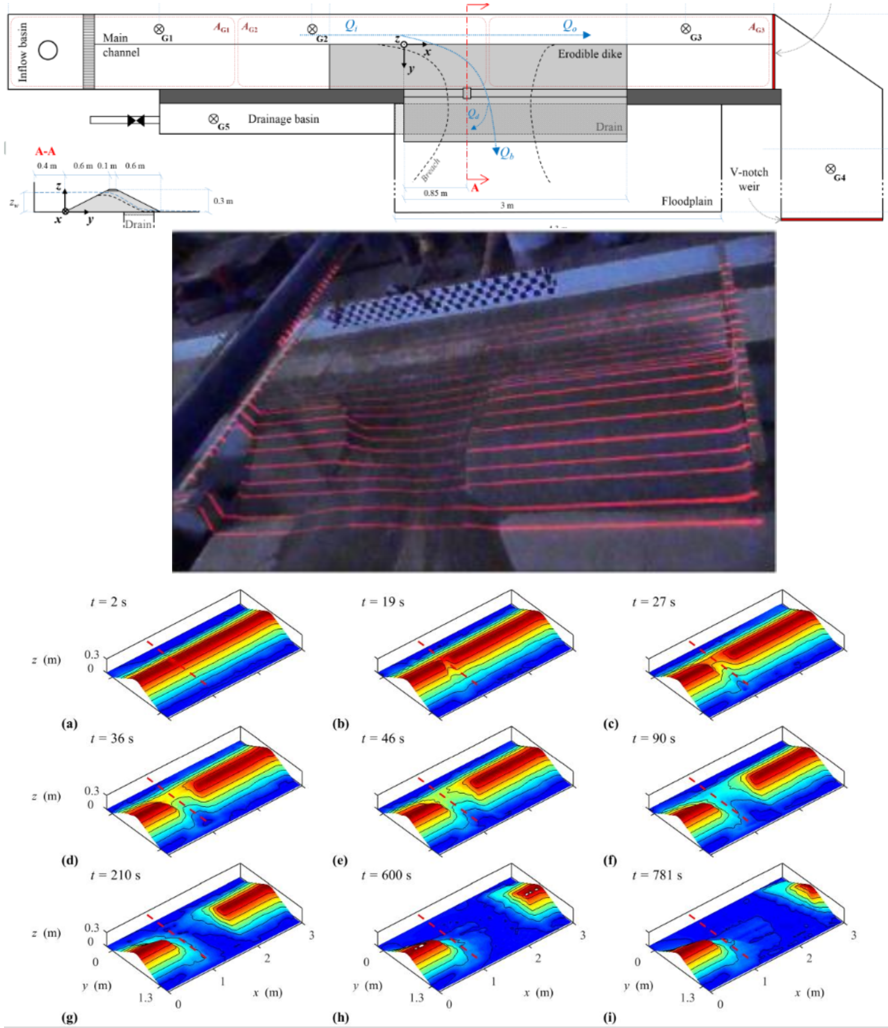


Failure mechanisms

EFFECT OF LONGITUDINAL FLOW

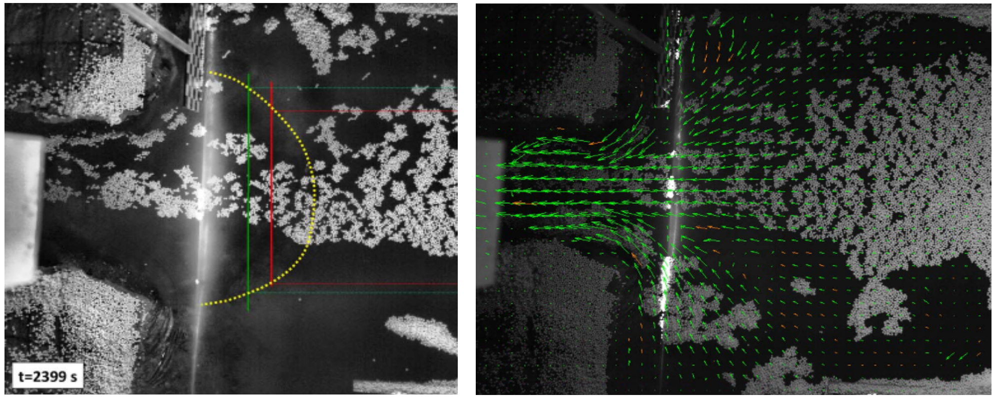


Kakinuma and Shimizu (2014): 4 large-scale tests on breaching of non-cohesive levees in an actual river channel



Rifai et al (2017): laboratory tests with homogenous levees of uniform sand

FLOW HYDRODYNAMICS AND BREACH MORPHOLOGIC EVOLUTION



- Amaral (2017): laboratory experiments with homogenous embankments dams of cohesive materials developed in LNEC. Analysis on the relation between the flow hydrodynamics and the morphologic evolution of the breach. Breach outflow was estimated using measurements of surface velocity fields in the breach vicinity and the geometric evolution of the breach area during the failure event
- **Observed that the breaching process is not symmetric, seeming to have an apparent alternate evolution (with mass instabilities occurring asymmetrically)**
- **Breach effluent flow increase is always gradual, rather than sudden**

MODELS FOR EMBANKMENT BREACHING

Empiric methods

MacDonald and Langridge−Monopolis (1984)

$t_f = 0.0179 V_{er}^{0.364}$ $\quad V_{er} = 0.0261(V_w h_w)^{0.769}$ **Earthfill**

$Q_P = 1.154(V_w h_w)^{0.412}$ $\quad V_{er} = 0.00348(V_w h_w)^{0.852}$ **Non-earthfills**

USBR (1988)

$B_{avg} = 3h_w$ $\quad t_f = 0.011\bar{B}$ $\quad Q_P = 19.1 {h_w}^{1.85}$ **(envelop eq.)**

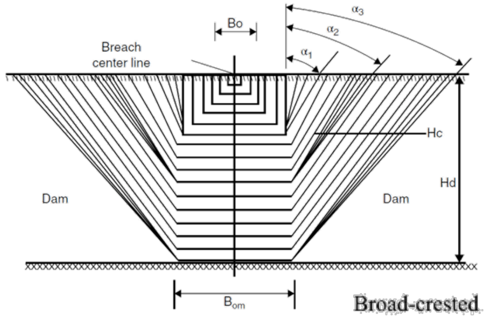
Based on dam-break failures databases

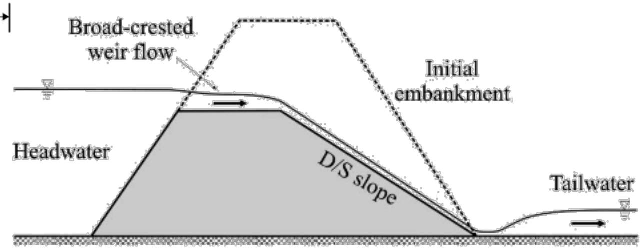
Very large uncertainties

Simplified physically-based models

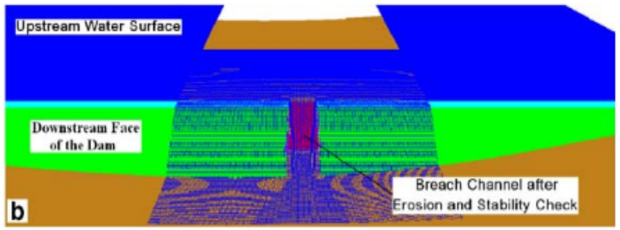
Breach evolution inconsistent with observations case studies and laboratory tests

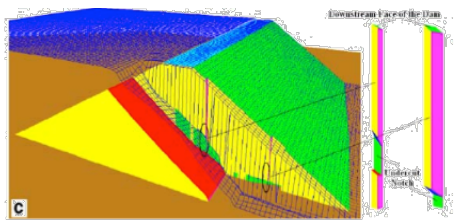
Outflow directly related with breach section





Detailed physically-based model





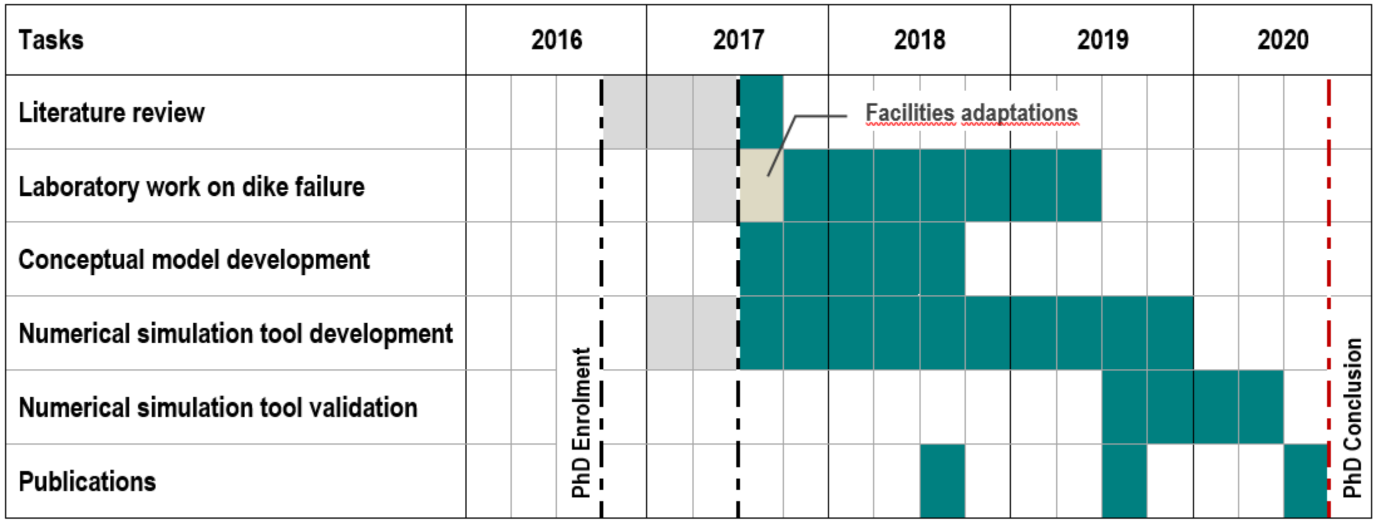
There is no generally accepted model for prediction of the headcut migration, and this mechanism is not implemented

High computational cost

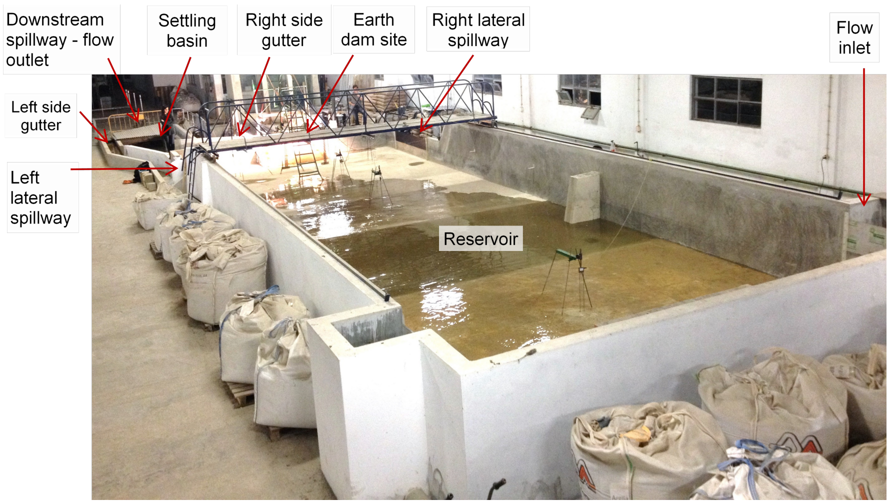
METHODOLOGY AND WORK PLAN

Research methodology of the PhD comprises the following main tasks:

1. Literature review
2. Laboratory work on dike failure
3. Conceptual model development
4. Numerical simulation tool development
5. Validation of the numerical simulation tool



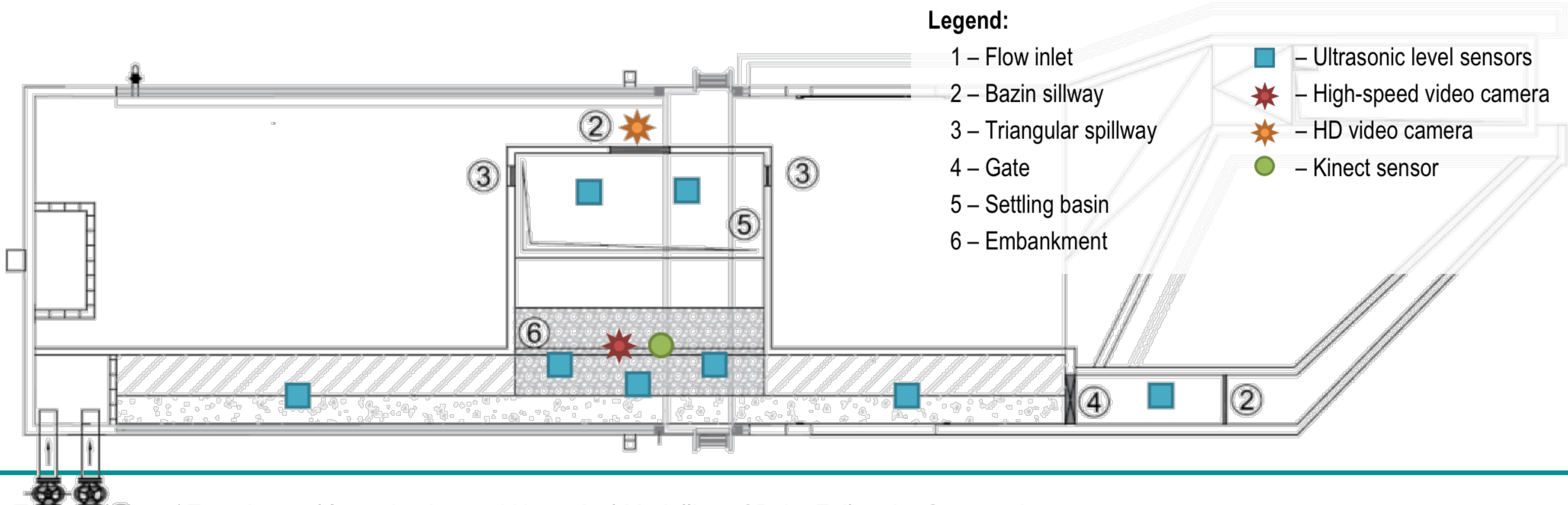
LABORATORY WORK ON DIKE FAILURE



Objective: perform a detailed empirical characterization of the breach evolution process:

- Hydraulic erosion/deposition processes
- Geotechnical failure episodes (mass instabilities)
- Local estimates of the breach hydrograph (i.e., based on proximity measurements)

Monitored parameters: main channel inflow; water levels (in the channel and settling basin); water surface elevation and surface velocity field in the breach vicinity; breach morphologic evolution and the detection of geotechnical failure episodes



Conceptual and Numerical Model Development

Data from laboratorial tests and previous studies

Conceptual model development

- Embankment conceptually separated from the sediment laden flow
- Conservation equations: derived from Boltzman equations (granular phase) and Reynolds Averaged Navier-Stokes equations (fluid phase)
- Closure formulae calibrated and/or corrected with laboratorial data

Numerical model development

- Built upon STAV 2D (shallow-water and morphological solver)
- Mathematical analysis of the PDEs to determine the number and nature of the boundary conditions
- Discretization with cell-centred flux-vector splitting FVD on an unstructured mesh
- Initial stage: blind-test of STAV2D with data of previous studies and laboratorial tests

Main concerns

Shallow water equations are not applicable to steep slopes

Geotechnical failure: determination of the yield surfaces and the creation of erosion cavities

Numerical model validation

- Preparing initial and boundary conditions
- Post process the results
- Comparing with field measurements

Field data of recent floods
Mondego river, 2013, 2016
Germany & Central Europe, 2013

Tank You!