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Levee Breach Modeling

The HR BREACH, AREBA and EMBREA breach prediction models

Jonathan Simm (for Mark Morris) USSD Oakland levee workshop Nov 2015

[1] Understanding breach growth

Three groups of key issues to understand

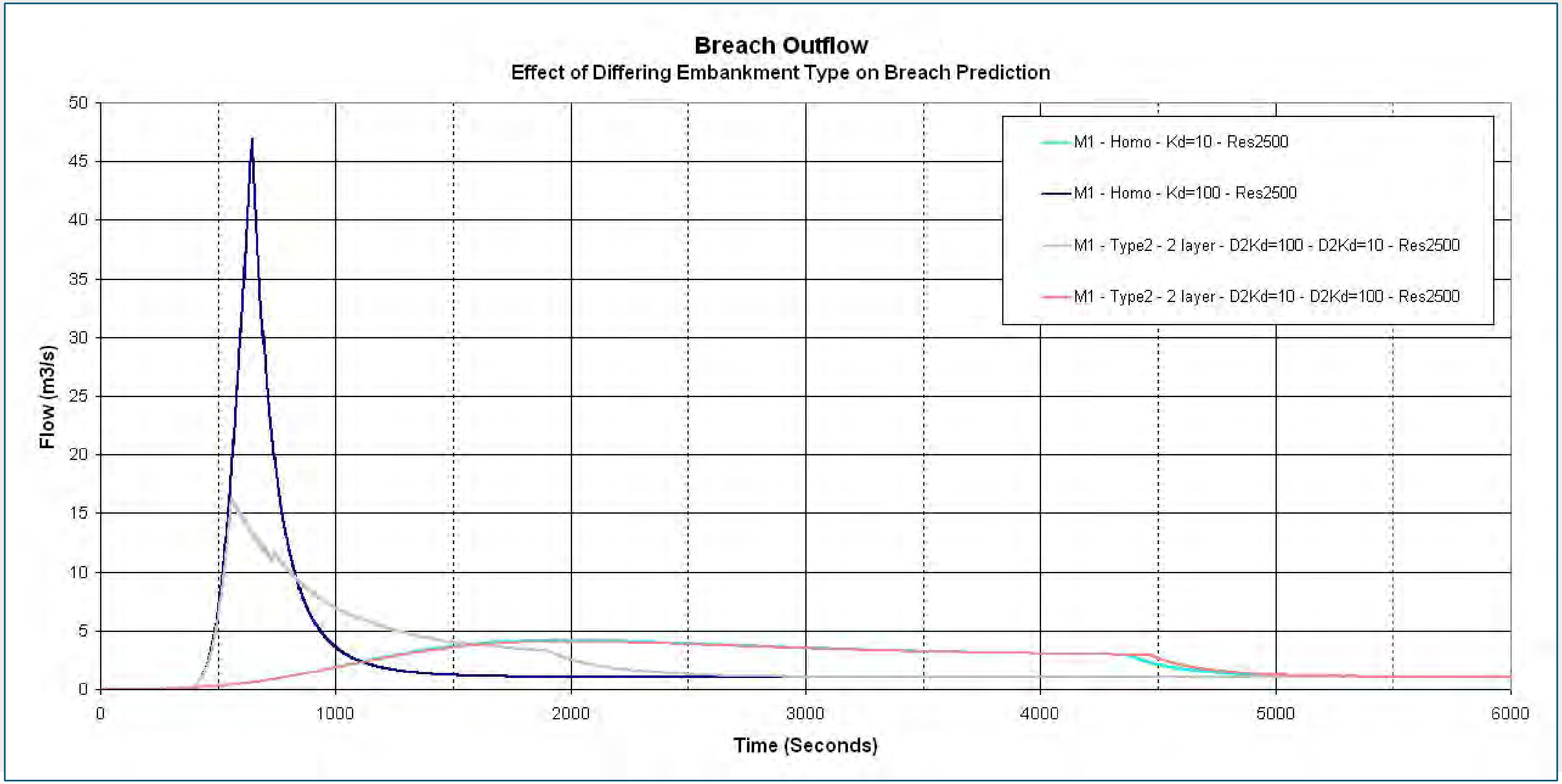
a) Soil erodibility (rather than conventional sediment transport formulations)

b) Breach erosion processes – headcut; surface erosion; internal erosion

c) Breach widening processes → breach shape / side erosion / block failure. (Models can predefine the sequence or let the physics determine)

(a) Soil erodibility

Soil erodibility affects the rate and nature of erosion – hence linked with hydraulic loading, it significantly affects the type of breach flow hydrograph.



(b) Erosion processes: Overflow - headcut

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Erosion processes: Overflow - headcut

a. Initial stages of headcut formation (11:55) – erosion at weak point near toe of slope

b. Formation of small headcut (12:07) near toe of embankment

c. Progressive erosion back of headcut from toe (12:32)

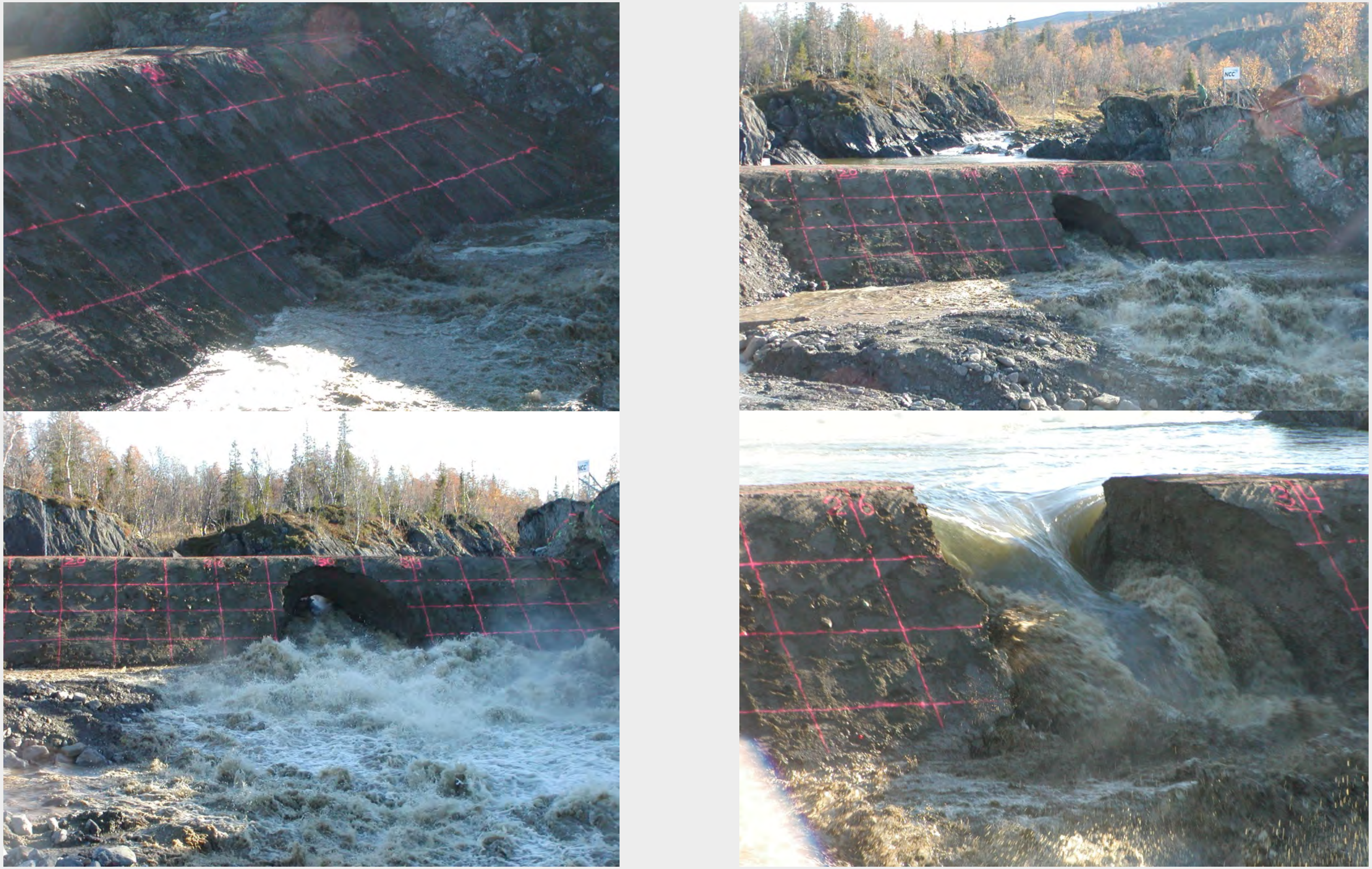
d. Erosion of headcut into single large step (12:39)

e. Progressive erosion of headcut (12:59)

f. Failure of upstream crest / slope (13:03)

Erosion processes: Overflow – surface erosion

Erosion processes: Internal erosion



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(c) Breach widening – shape & erosion process

a. Tension crack forming in crest; embankment ends rotating into breach

b. Tension cracks develop into block failure. Pressure of flow sliding and rotating blocks

c. Soil block fails and rotates into breach flow (removed completely within 10s)

d. Breach sides remain vertical or undercut during the breach formation process

Breach widening – shape & erosion process

c. Flow converging to point shortly after erosion cuts through upstream crest

d. Flow vortices and undercutting along the toe of each eroding breach face

a. Headcut erosion back through dam after failure of the spillway (El Guapo Dam, Venezuela)

b. Vortices undercutting the breach sides just after failure of the spillway crest (El Guapo Dam, Venezuela)

[2] Why model breach growth?

The way and rate at which a levee or dam breaches affects the timing of the breach, the rate and magnitude of the flood water released and the size of the breach itself.

Therefore, breach affects the analysis of flood risk and can change the way in which flood events might be managed.

Understanding the degree of uncertainty within the process and any prediction is a very important aspect of using breach predictions

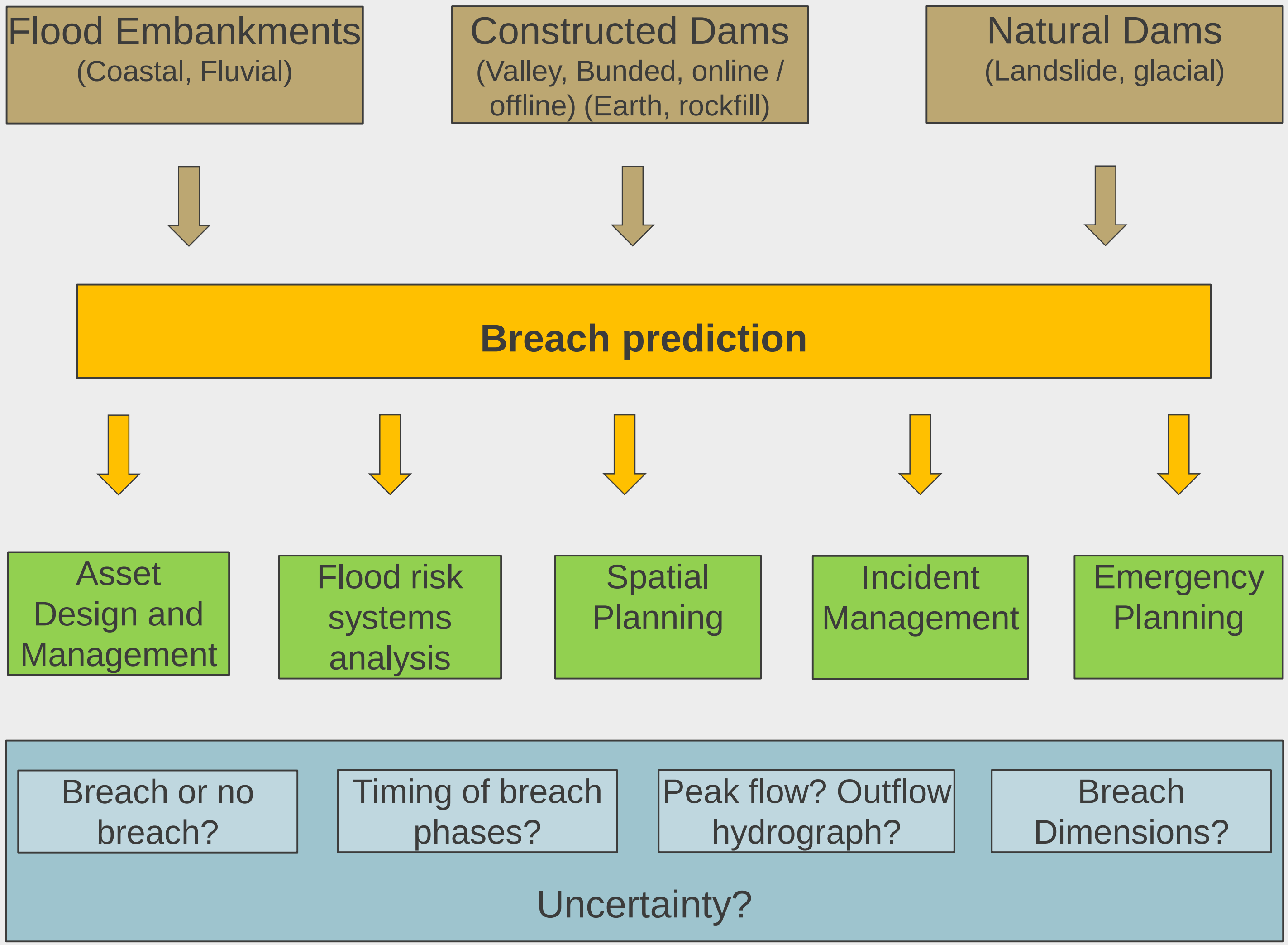
Model development – What and why?

Different end users each with:

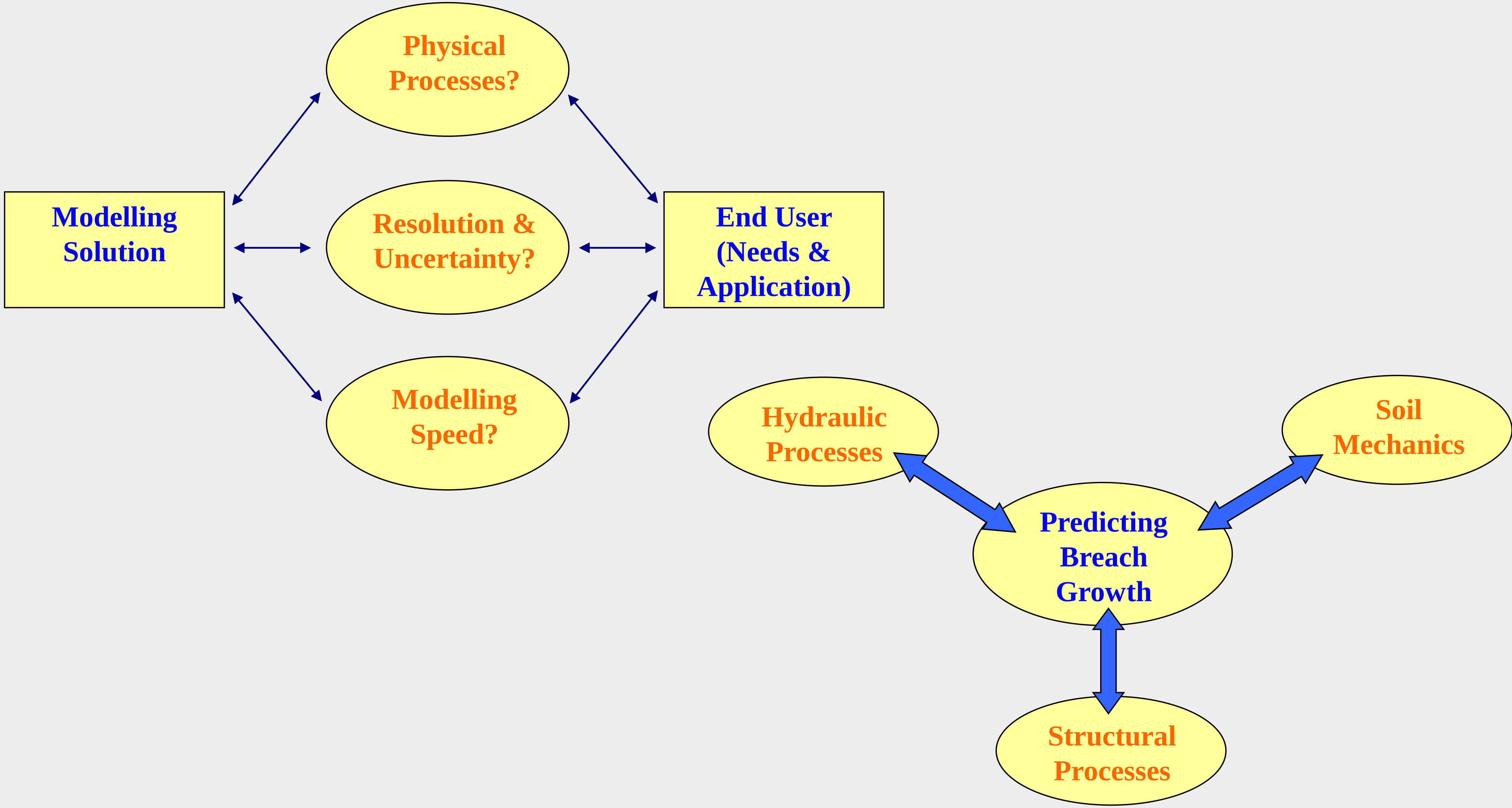
- •different needs
- •different priorities
- •different acceptability of uncertainty

Requires a range of different methods and prediction:

- **•Speed**
- **•Accuracy**
- **•Nature of outputs**



Model development:
Keep in mind...and in balance...



Model development – What?

In the UK we have been working on breach prediction methods since the mid 1990s:

1. Initial recognition of need for breach model(s) ~1995 in response to dambreak studies
   - Reviewed NWS BREACH and decided to develop a new, more physically based approach
2. HR BREACH model – Mohamed, ~1998-2002
3. HR BREACH testing and evolution, Mohamed / Morris, 2002 → 2008
4. AREBA model – van Damme, ~2009-2011 [Validated against HR BREACH]
5. EMBREA model – Morris, ~2011 [evolution from HR BREACH]

Model development – What?

HR BREACH (2002-2008)

- The original model
- Physically based - 1D flow; free format breach shape with side block failure process
- Surface, headcut and piping erosion options [headcut = USDA Simba methodology]
- Rock and grass surface protection
- Composite structure (core failure option)
- Integrated inside InfoWorks RS2D flow model (2008)
- Used in DSIG breach modelling test programme (Wahl)
- Predictive, time stepping model; *minutes* to run; output hydrograph and breach shape
- Monte Carlo option for sensitivity analysis

AREBA (2009-2011)

- Simplified model (compared to HR BREACH). Similar concept to SIMBA (WinDAM)
- *Fast* run time – less than 1s
- Predefined failure processes
- Surface erosion, headcut and piping erosion options

- Developed to support system risk modelling, where thousands of calculations are needed in a short time

EMBREA (2006-2012)

- Evolution from HR BREACH

- Modelling of **layered levees and dams** (different soil erodibility in different geometries)
- Refined modelling details

Model validation

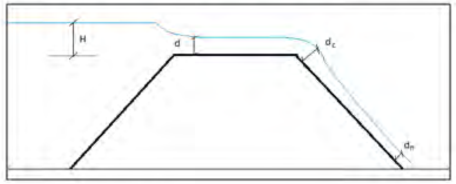
Model validation:

- Model performance compared against data from a mixture of laboratory, field and real case studies – covering a range of material and structure types
- Models are NOT calibrated to one particular case or data set

- Example of data used:
  - European research project data – IMPACT field and laboratory case
  - CEATI Dam Safety Interest Group breach modelling project
    - IMPACT / ARS / Real dam studies
  - Real dam failures

- 1D flow behaviour
- Downstream slope retreats through the embankment before widening (surface erosion) f.e. BRES model (Visser 1997)
- No lowering of the crest level before the headcut has reached the upstream slope. (SIMBA) (Temple & Hanson (2005))
- Breach widening rate is a function of the rate at which the crest lowers. (HR BREACH, SIMBA) Mohamed (2002)
- No equilibrium transport conditions (SM, HR BREACH)
- Instantaneous failure grass cover (HR BREACH, SM)
- Soil erodibility is equal along the embankment and constant in time (BRES, HR BREACH, SM)
- Slope gradient of the inland slope is limited (BRES, SM)
- Fixed side slope assumptions (BRES, SM, SIMBA)

Constitutive equations surface erosion



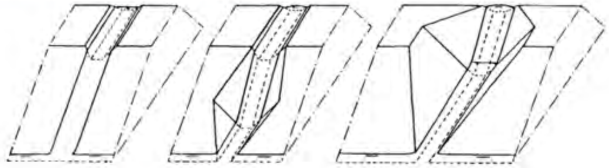
Erosion equation: $E = K(\tau - \tau_c)$

Shear stress relation: $\tau = \rho u^2 \frac{n^2 g}{d_n^{1/3}}$

Function shear stress along slope: $\tau(x) = \rho \left(\frac{1}{\left(-a e^{\frac{x-x_0}{L}} + a + e^{\frac{x-x_0}{L}}\right)^2} \right) u_c^2 \frac{n^2 g}{d_n^{1/3}}$

Where: $a = \frac{g^{1/3} n^{2/3}}{d_e^{1/9} i_b^{1/3}}$

and $L = \left(\frac{1}{3 i_b} - \frac{d_n^{1/3}}{3 g n^2} \right) d_n$



Source: Visser (1998)

Constitutive equations Headcut erosion

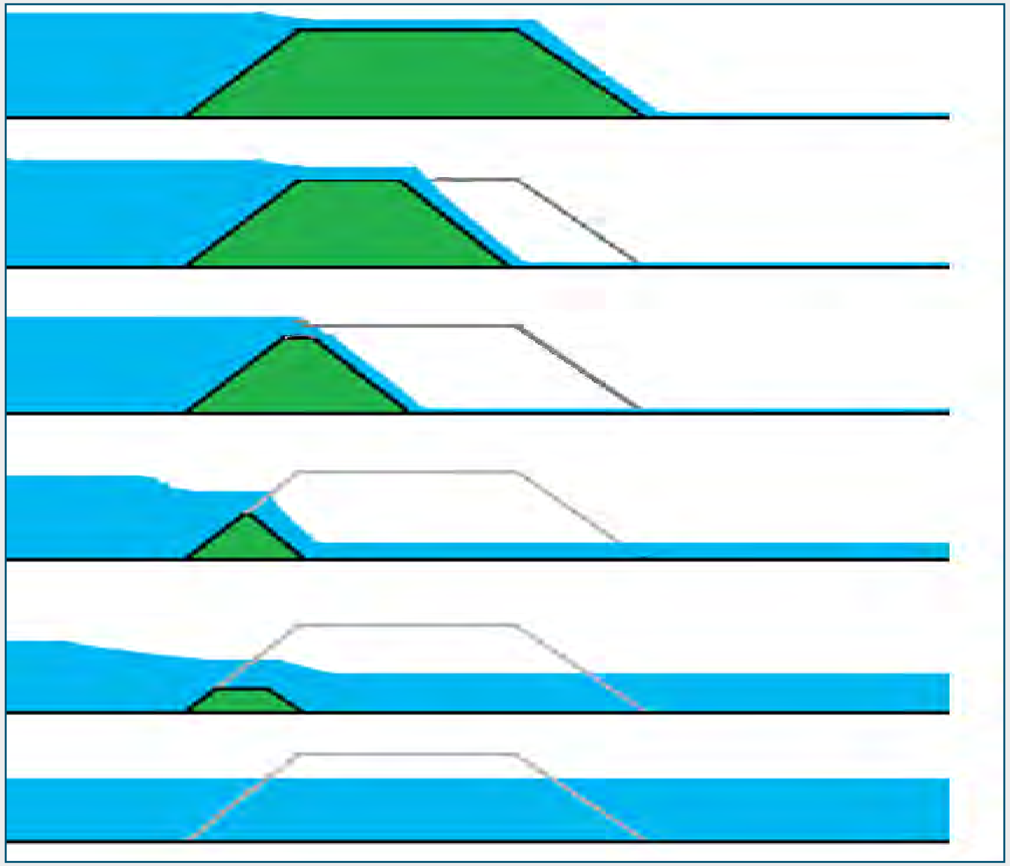
Erosion equation: $E = K(\tau - \tau_c)$

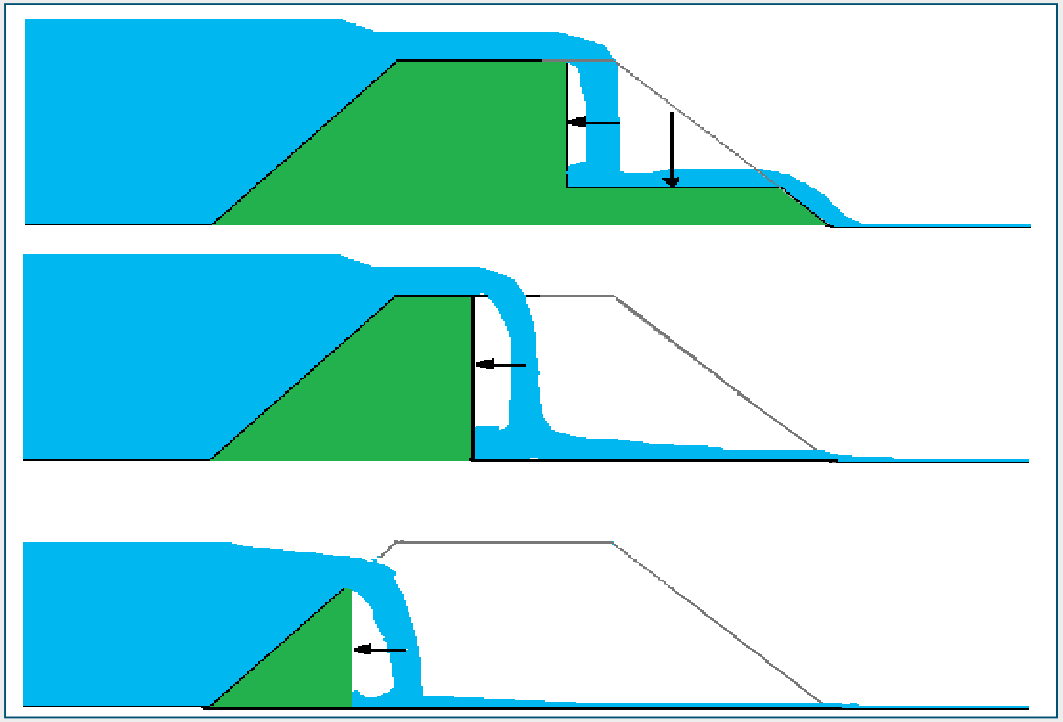
Headcut advance rate: $\frac{dX}{dt} = C(q \cdot h_{hc})^{1/3}$

Shear stress relation for overfalling water: $\tau = \rho g d_c \cdot 0.011 \left(\frac{h_{hc}}{d_c}\right)^{0.582}$

- Headcut starts at the top of the inland slope (SIMBA, SM)
- No erosion below the foundation of the embankment (HR BREACH, SM)

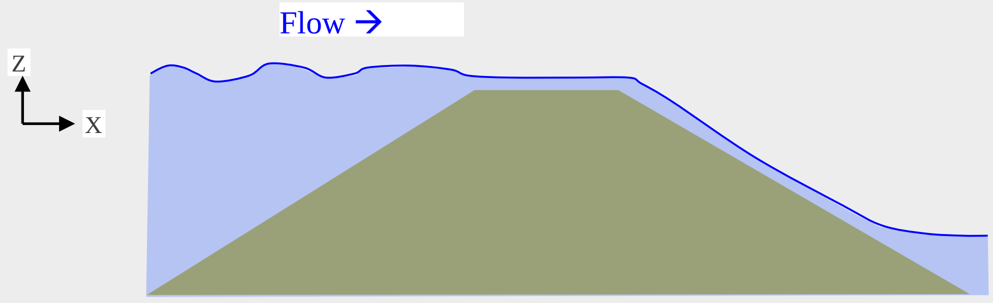
AREBA

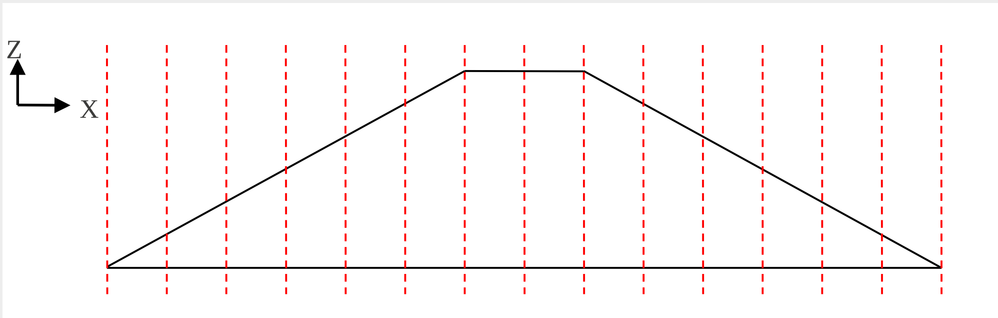


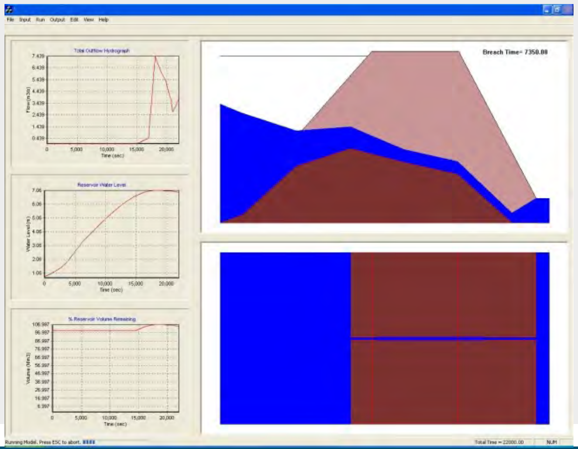


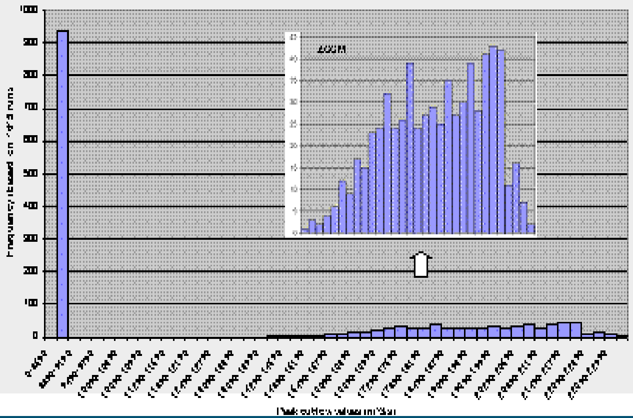
Developed from HR BREACH:

- Homogeneous or composite structures
- Option for grass / rock surface protection
- Overtopping or piping initiation
- Surface erosion or headcut progression
- Graphics show growth of breach during simulation
- Selection of erosion or sediment transport equations
- Capability for Monte Carlo analysis

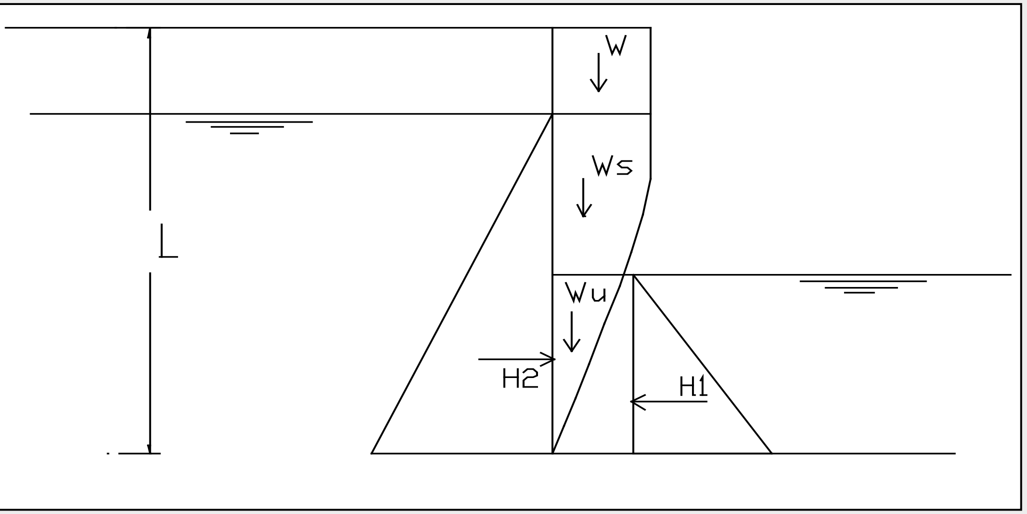




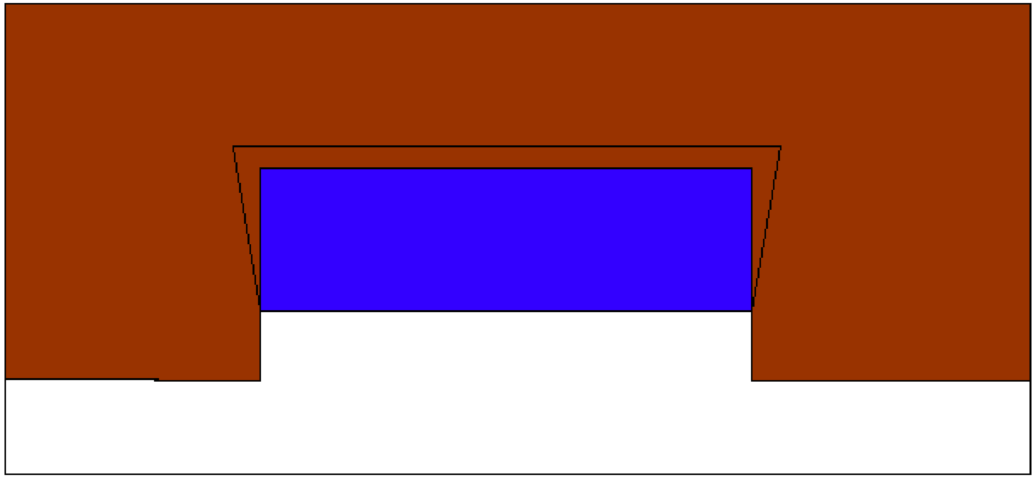




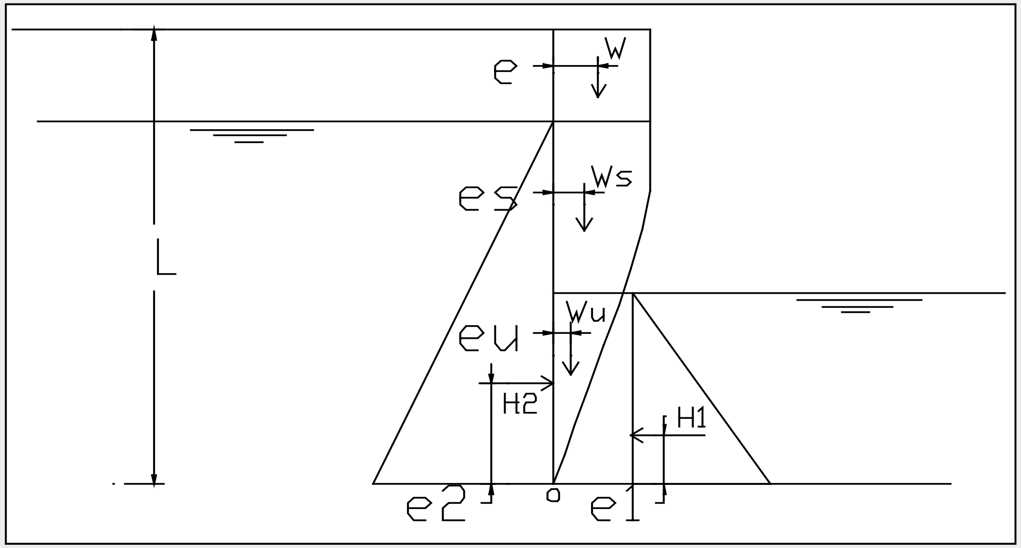
EMBREA – Shear failure

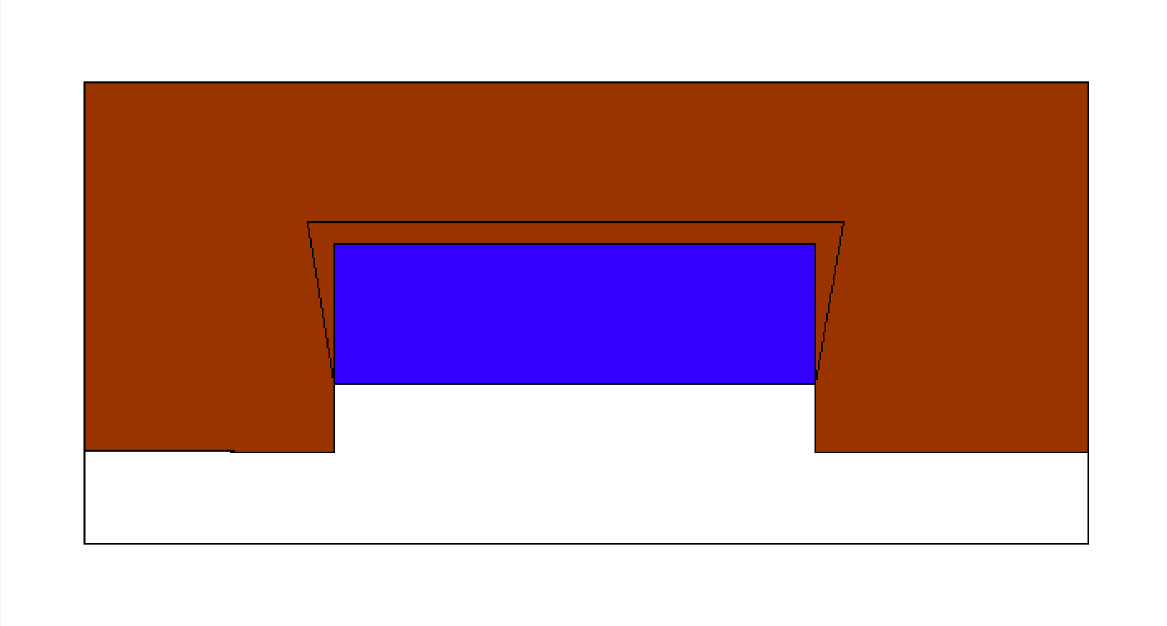


$$FOS = \frac{c * L + H_1 \tan \phi}{W + W_s + W_u + H_2 \tan \phi}$$



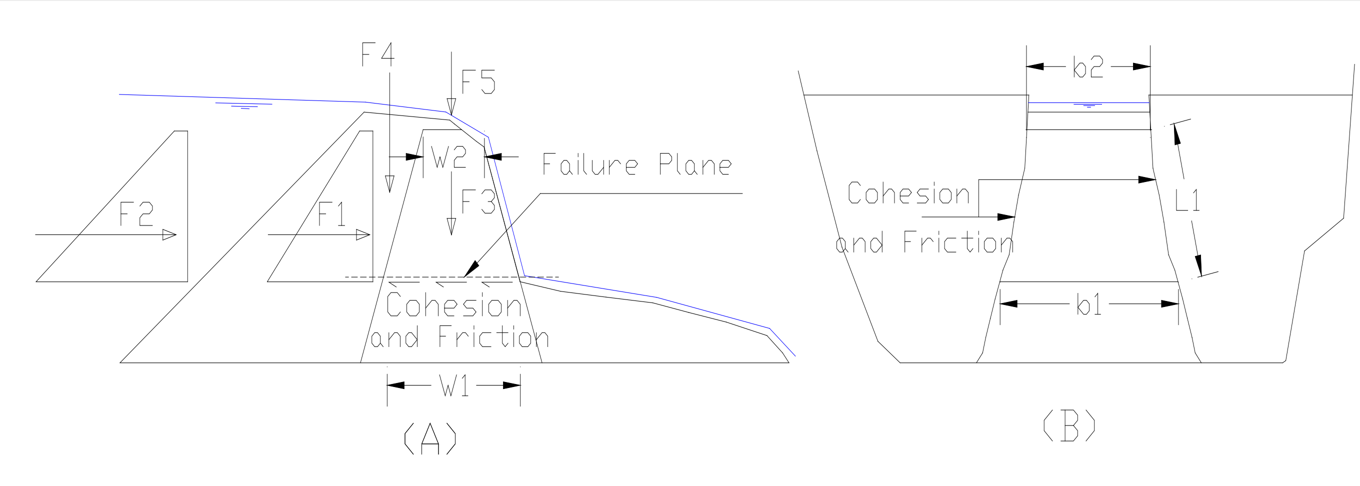
EMBREA - bending failure

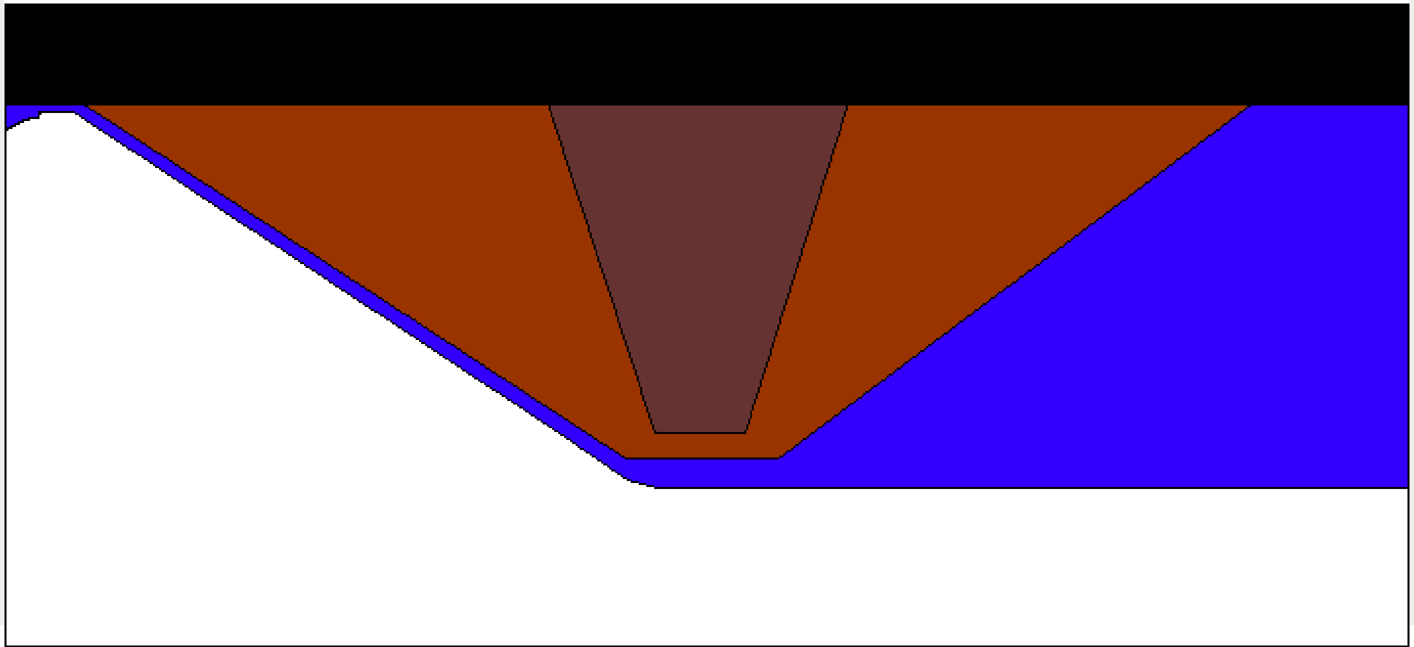




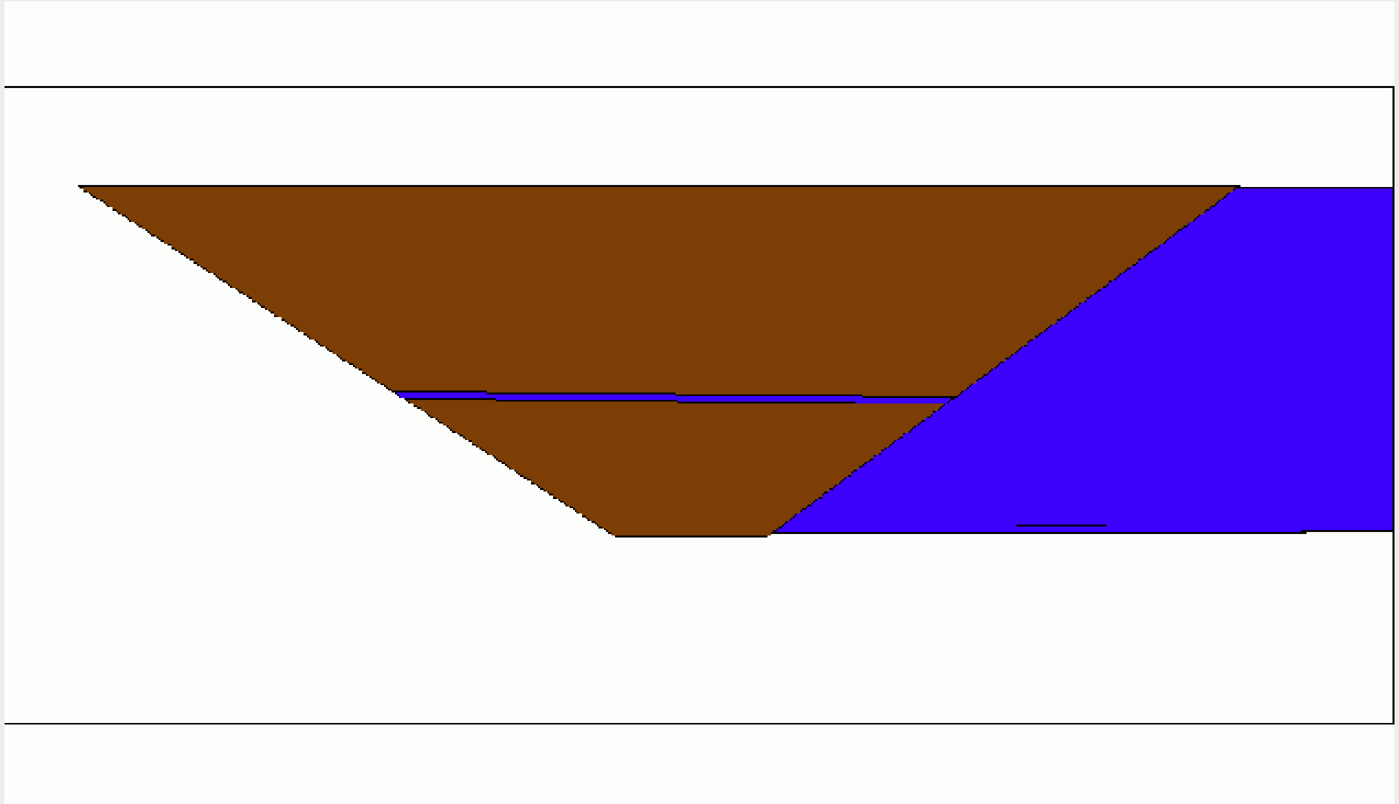
$$\sigma_{t(actual)} = (H_2 - H_1)/d + 6M_0/d^2$$

EMBREA – composite failure





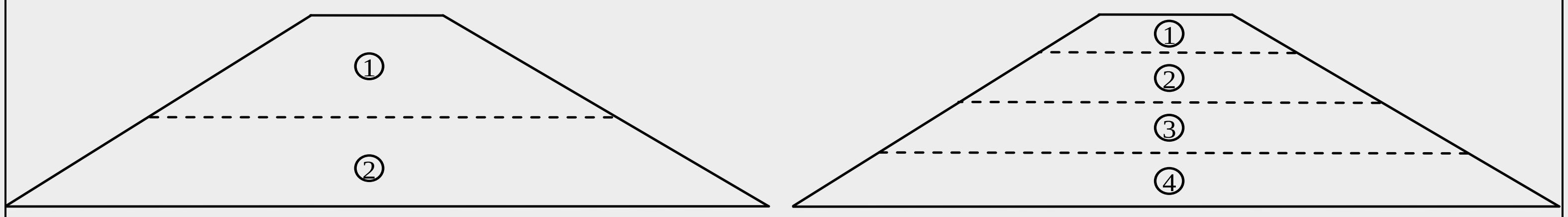
EMBREA – internal erosion failure



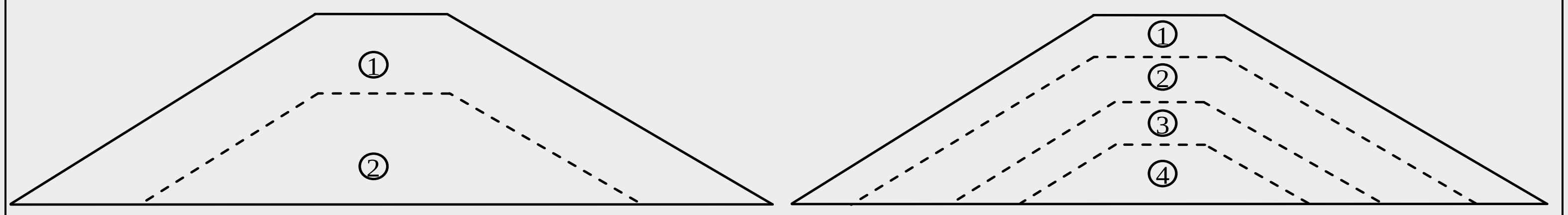
EMBREA – Layered / zoned levees and dams

Additional Processes Simulated by the New Modelling Approach

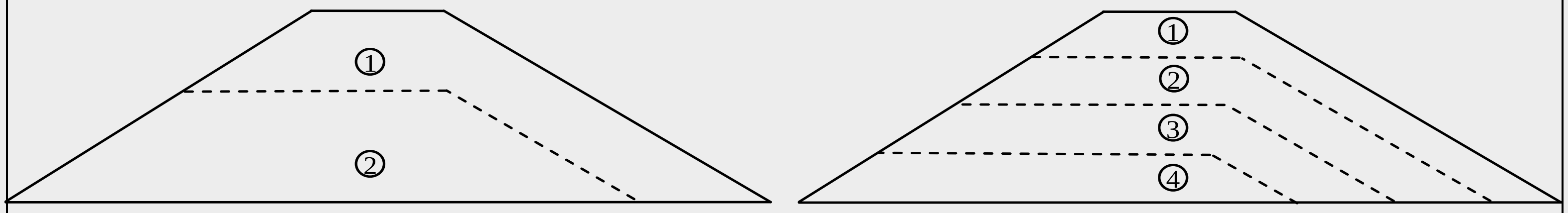
Simple Layered – Type 1 (Surface erosion)



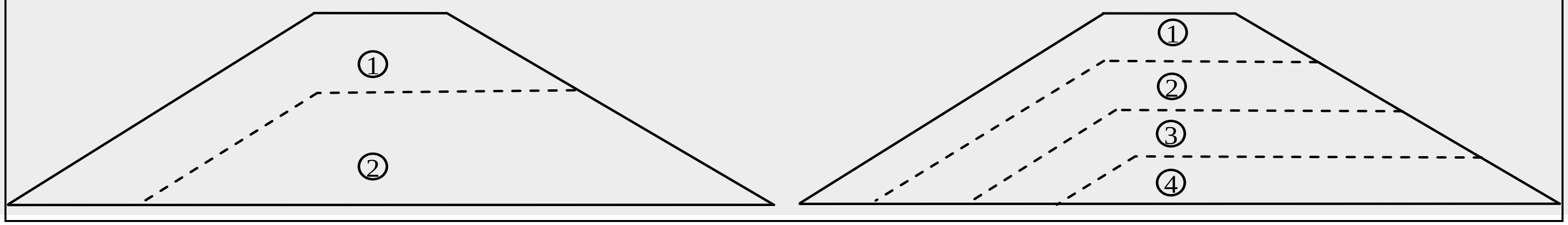
Stacked Layered – Type 2 (Surface erosion)



Enlarged Outward Layered – Type 3 (Surface erosion)



Enlarged Inward Layered – Type 4 (Surface erosion)



EMBREA – base run - homogeneous

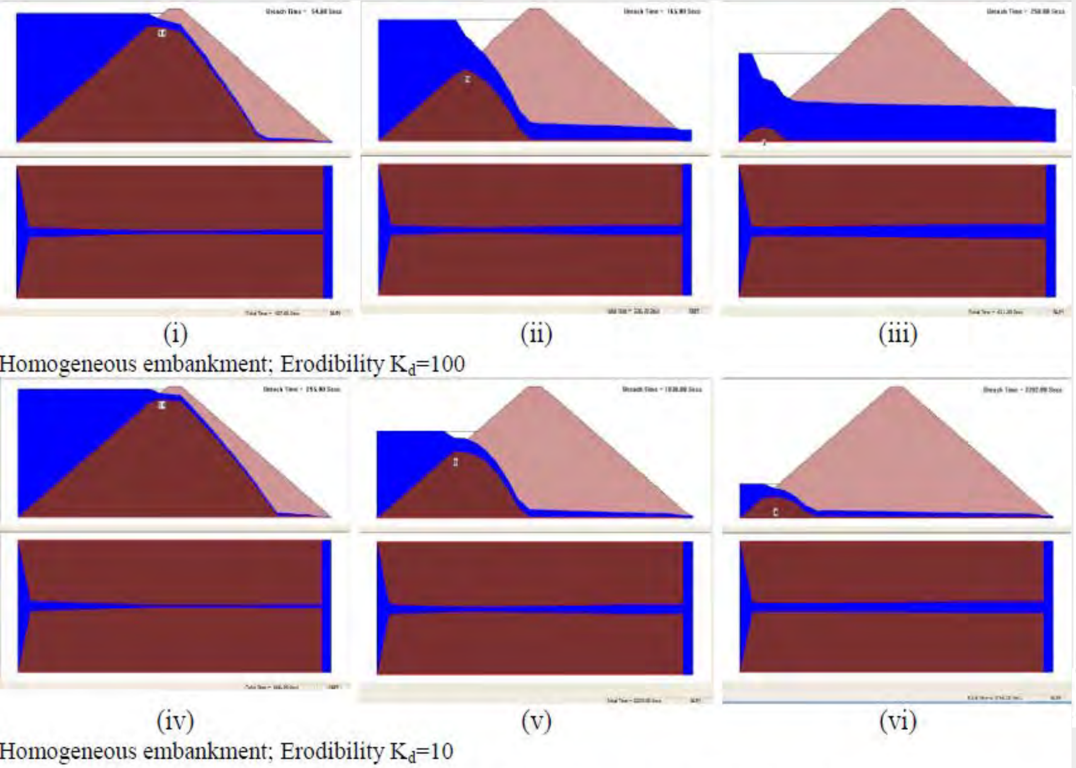


Figure 7-11 Model simulation of breach growth for homogeneous embankment

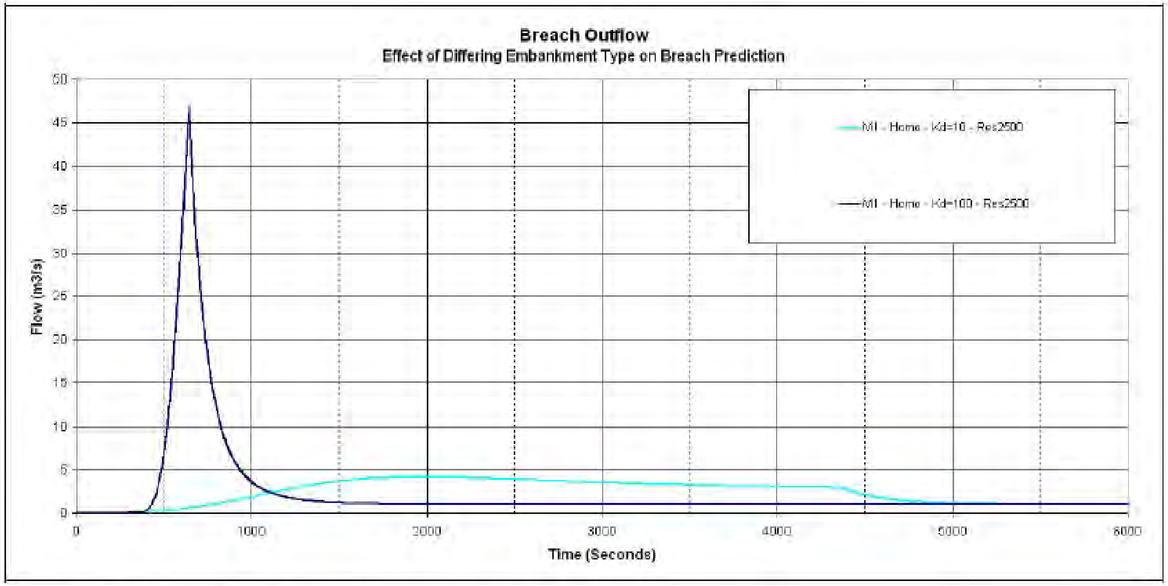
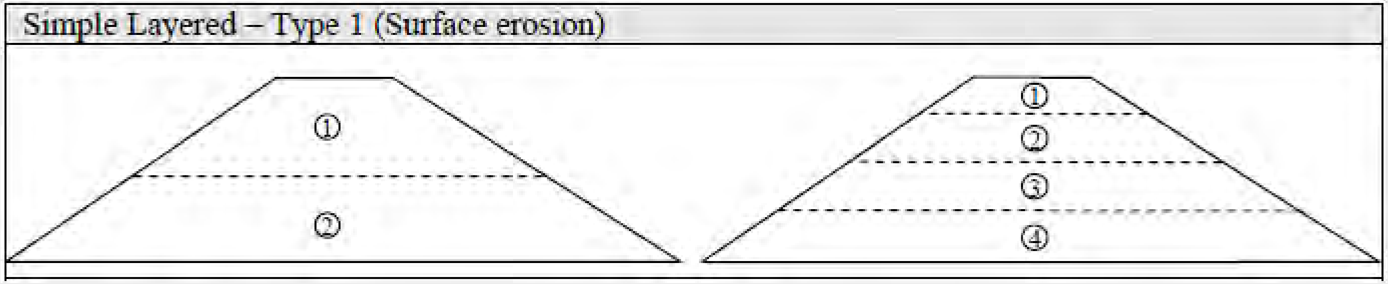
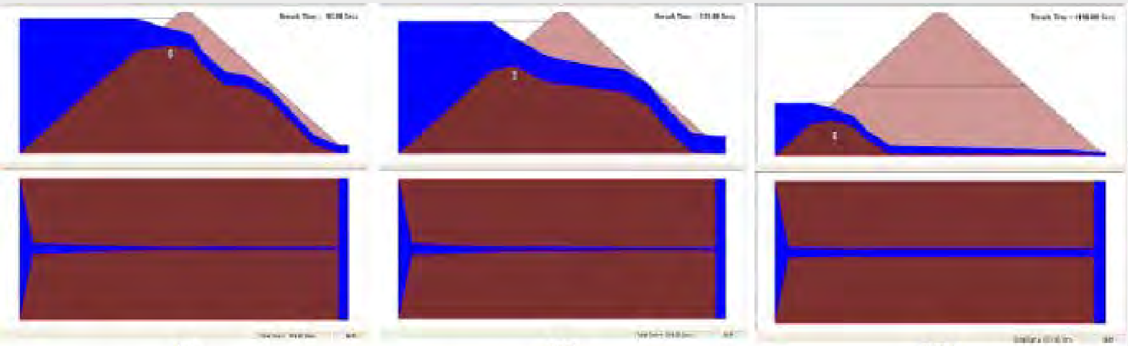


Figure 7-12 Breach outflow: Homogeneous embankment

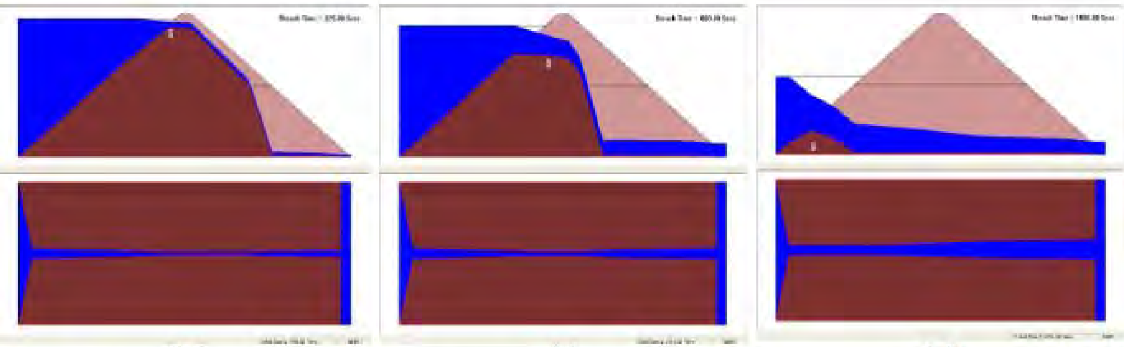
EMBREA – Type 1 – 2 layers





(i) (ii) (iii)

Type 1, 2 layer embankment: Layer 1= 2m, K_d=100; Layer 2 = 2m, K_d=10



(iv) (v) (vi)

Type 1, 2 layer embankment: Layer 1= 2m, K_d=10; Layer 2 = 2m, K_d=100

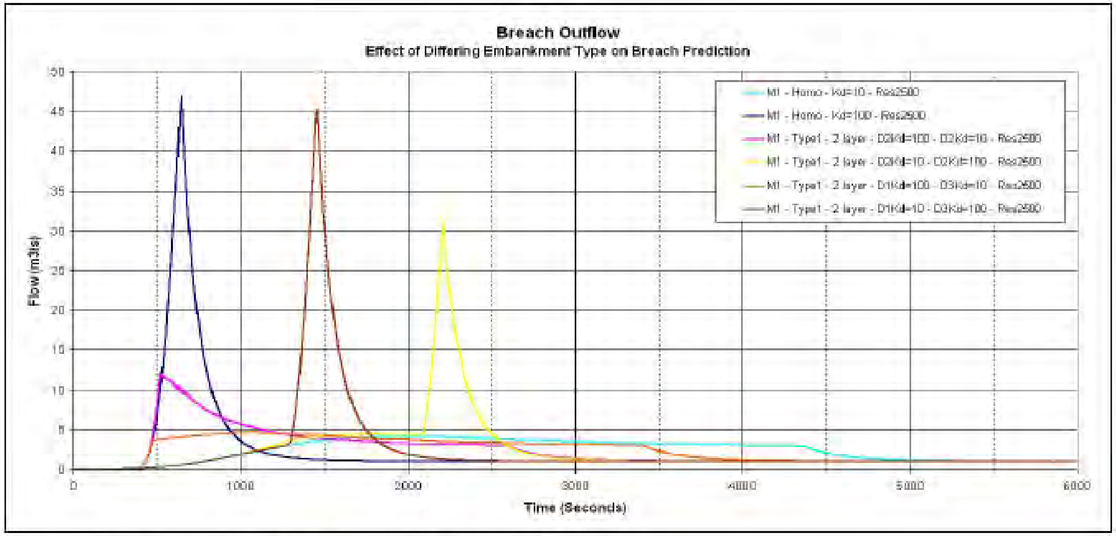


Figure 7-15 Breach outflow: Type 1, 2 layer embankment

EMBREA – Type 1 – 2 layers

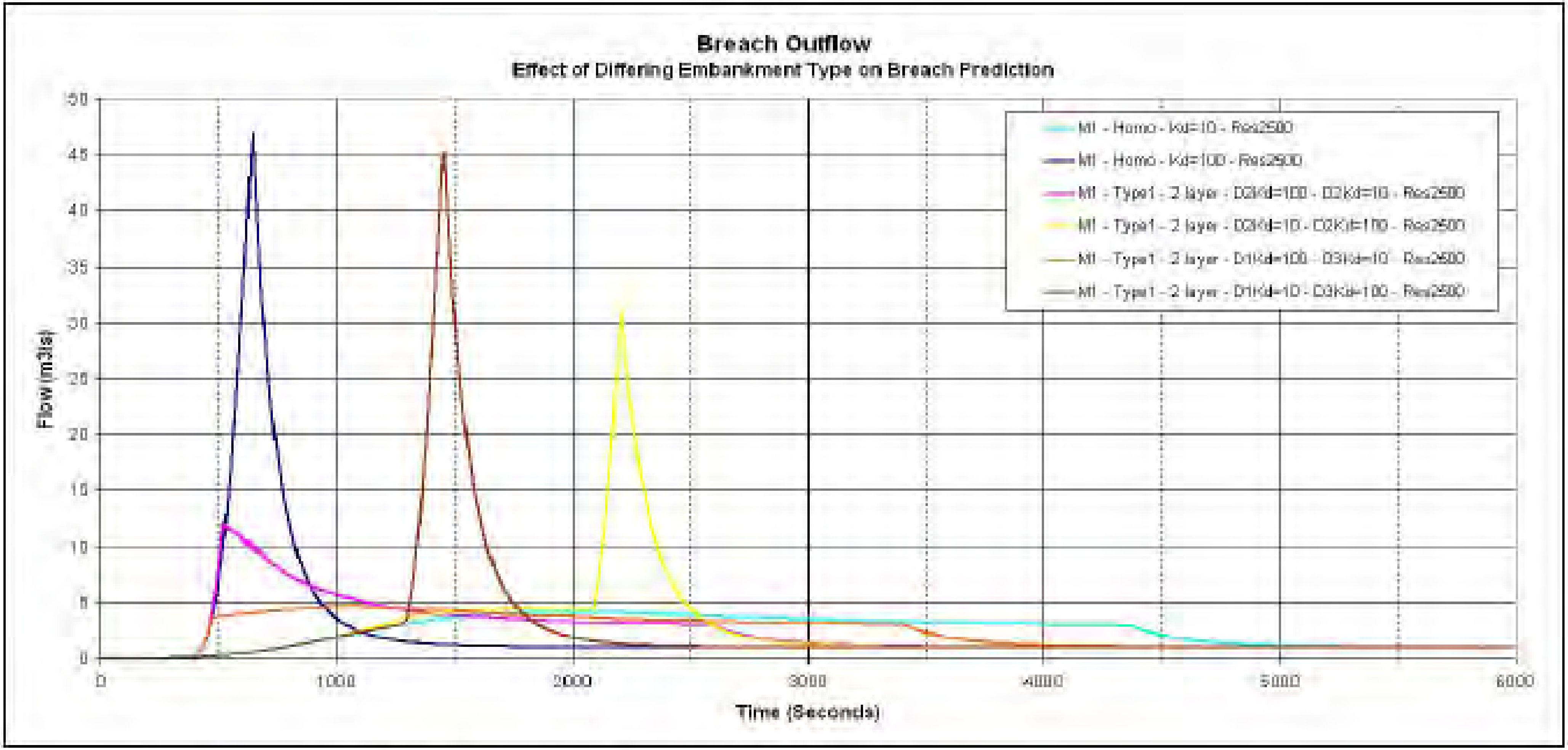


Figure 7-15 Breach outflow: Type 1, 2 layer embankment

[3] Conclusions

Some key issues for further research:

Physical Processes:

1. Soil erodibility – understanding absolute; natural and man made variability
2. Headcut / surface erosion – transitions – when / why?
3. Real geometries (zones – layers etc) – significance and effect?

Choosing the right method:

1. Time and place for each of the methods (engineering judgment, regression analyses, simple models, more complex models)
2. Understanding the acceptable degree of uncertainty (ensuring consistency in uncertainty and resolution through flood modelling, mapping and impact assessment).

[4] Future direction

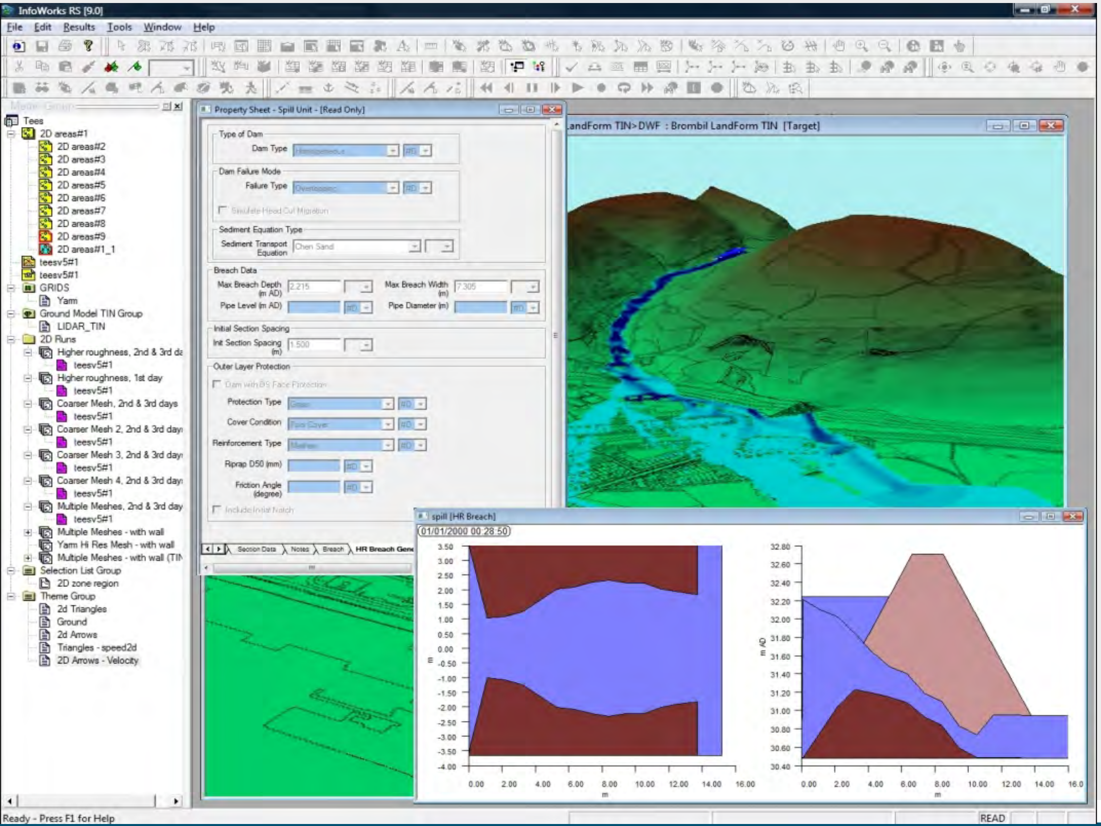
Some research and development priorities:

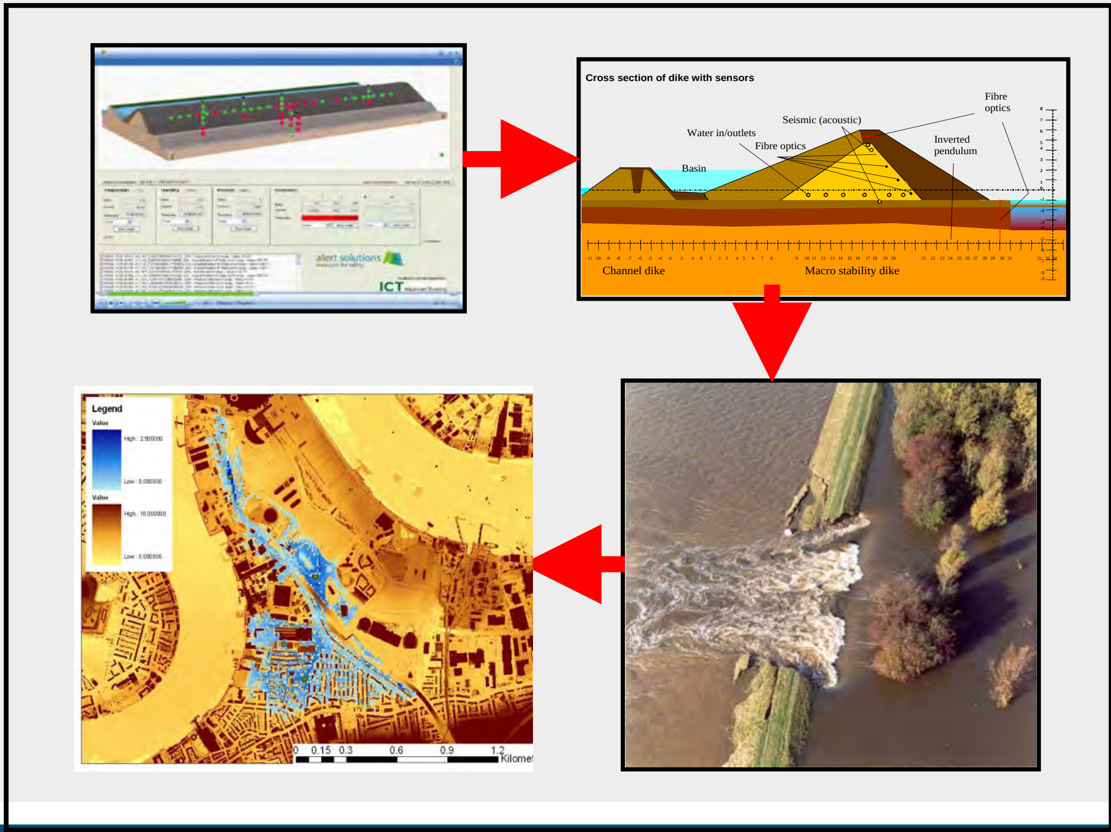
1. Establishing *reliable breach model parameters* (e.g. How to estimate and measure soil erodibility (for both cohesive and non cohesive soils)
2. Understanding how soil erodibility influences breach processes – headcut versus surface erosion processes – when and why?
3. Validation of breach prediction methods for non cohesive as well as cohesive materials (levees are made from all sorts...). Validation of generic applicability of the excess stress equation.
4. Predicting breach through real geometries (zones – layers etc) – significance and effect?
5. Understanding natural and man made variability in soil erodibility

All supporting the development of validated, practical tools for the prediction of breach conditions...

Future direction:

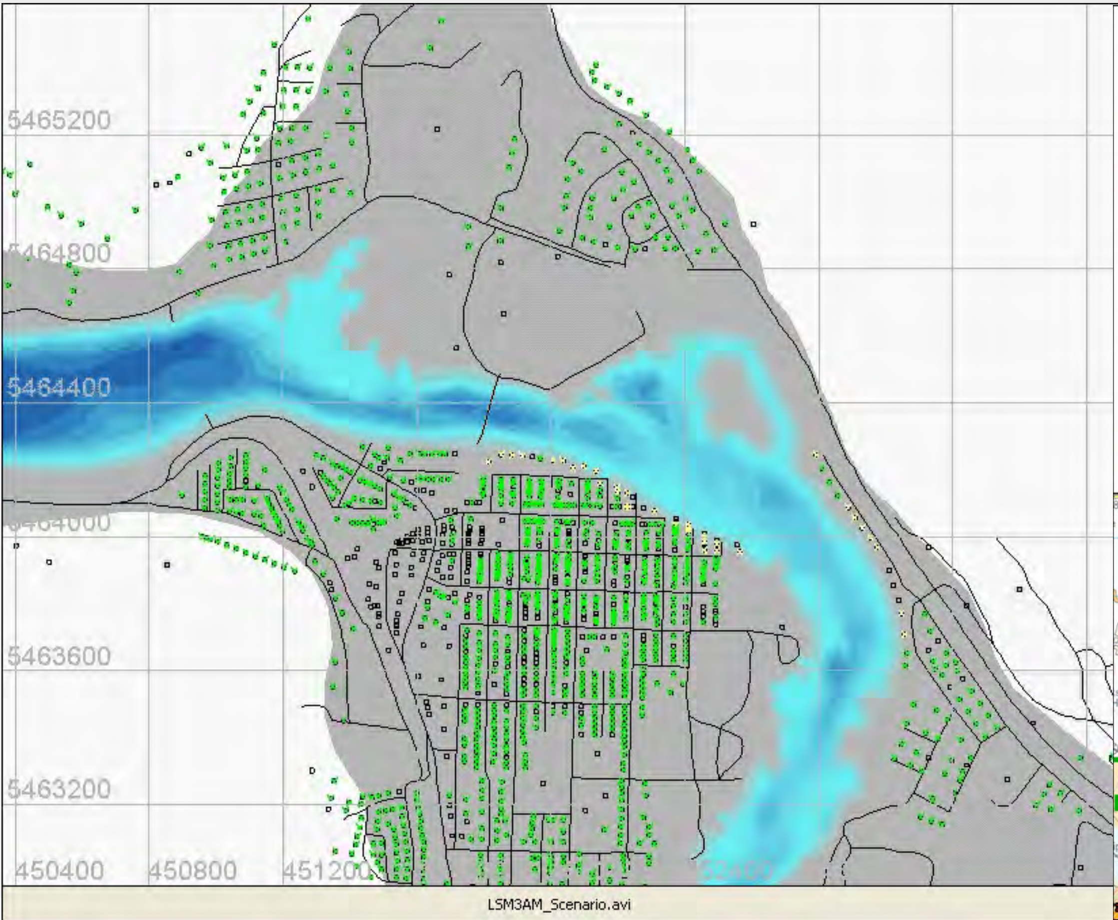
- Model linking / integration with 2D flow models
- Smart systems / system risk monitoring and analysis (e.g. European UrbanFlood project)

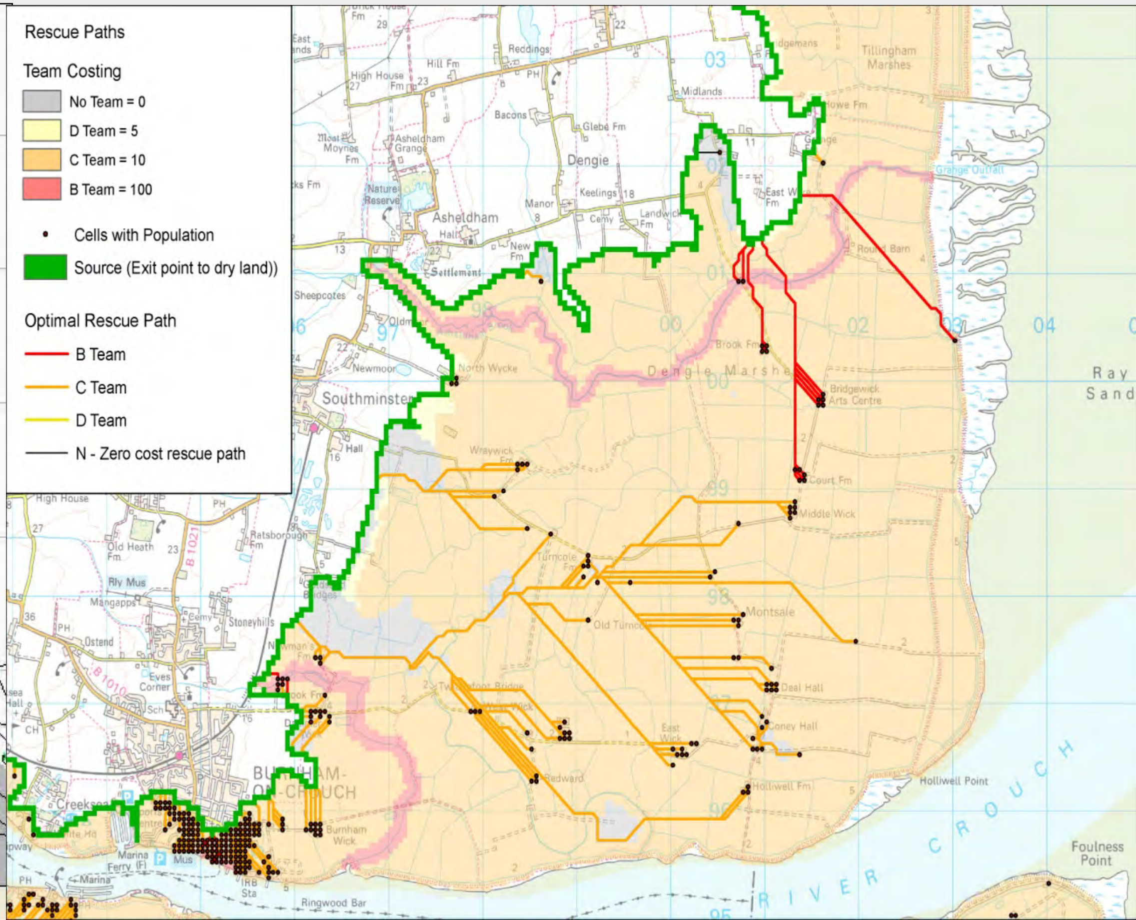




Future direction:

- Integrated models – life safety modelling
- Integrated models – emergency response resource planning





Levee Breach Modeling questions

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Model development – The bigger picture