**Rémy Tourment**

**Rémy Tourment** is an engineer-researcher with the Hydraulic Works Research Unit of Irstea since 1989. He is an expert on dam and levee safety and is now coordinator for research and expertise. Since 2009, Rémy acts as project manager and major contributor for various research projects related to levee safety and performance assessments as well as flood risk analysis. These include the French project DIGSURE, the EU FP7 project FloodProBE, levee-related flood risk analyses as well as contributions to the International Levee Handbook (ILH). Rémy is also Chairman of the Levees Technical Committee of ICOLD.

# Levee failures and internal erosion mechanisms: the role of risk analysis

Levee system risk analyses are becoming commonly used to inform decision making in terms of levee upgrading or maintenance, of protection systems management as well as of flood risk management. A framework for these analyses has been defined in the International Levee Handbook (ILH). Levee failure mode analysis is an integrated part of the levee system risk analysis. It allows the identification of different failure scenarios involving more than one mechanism.

ICOLD Bulletin 164 describes different phases in a dam or levee failure scenario as well as four different internal erosion mechanisms. After a brief overview of the ILH, this presentation will show different examples of levee failure scenarios involving one or more internal erosion mechanisms. Using experience from the FloodProBE project, this presentation will show how these mechanisms can interact. It will also show how to better integrate the available knowledge on internal erosion and failure modes analysis to improve levee sytem risk analyses for better decision making.


# Levee failures and internal erosion mechanisms: the role of risk analysis

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CDA ACB
Canadian Dam Association
Association canadienne des barrages

# Contents of the presentation

- Introduction: levee system risk analysis
  - Risk: what is it – relativity of the point of view
  - The ILH framework
  - Use in decision making
- Levees failure modes – hydraulic/structural - deterioration-damage-breach – scenarios – failure modes analysis
- The roles of internal erosion mechanisms in RA and FMA :
  - Process / Scenario / failure path / failure mode
  - Different mechanisms
  - From the material scale to the structure scale
- Example of failure scenarios involving internal erosion
  - Different IE mechanisms (FloodProBE)
  - Other mechanisms before IE
  - Other mechanisms after IE
- How to use Bulletin 164 in practice in a risk analysis
  - Estimation of failure probability
  - Barriers : filters and auto-filtration
- Conclusions and perspectives
  - ISSMGE TC 201

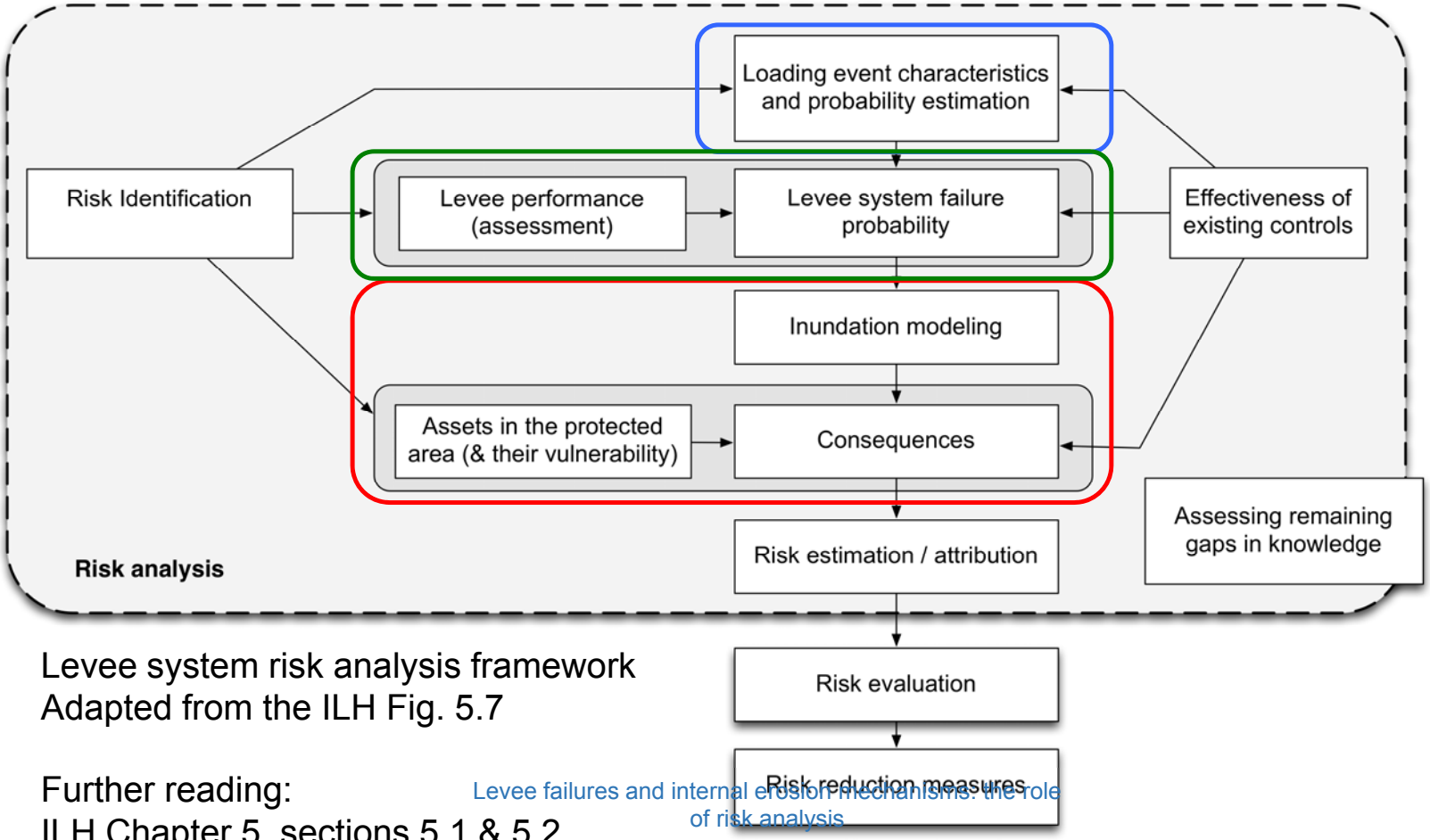
# Introduction: what is “Risk”?

- Risk = hazard (x) consequences
- Hazard : dangerous event (threat) with an associated probability
- Vulnerability = damage associated to the intensity of  the threat

- In the case of levee systems:
  - From the point of view of the population and other stakeholders of the protected area:
    - risk = risk of flood in the protected area
    - hazard is a combination of a natural hazard (river flood, storm, …) and a technological hazard (levee system failure)
    - vulnerability: of the people and assets in the protected area to flooding
  - From the point of view of the levee managers:
    - risk = risk of levee damage or failure
    - hazard = natural event loading the levee
    - vulnerability: of the levee and associated structures to the natural event (river flood, storm, waves, …)
  - Consequences of failure (flooding) may differ a lot more than in the case of dams, according to the failure scenario (location of a breach in a long system)

Further reading: ILH Chapter 2, section 2.1

# Introduction : levee system risk analysis




Source

Pathway

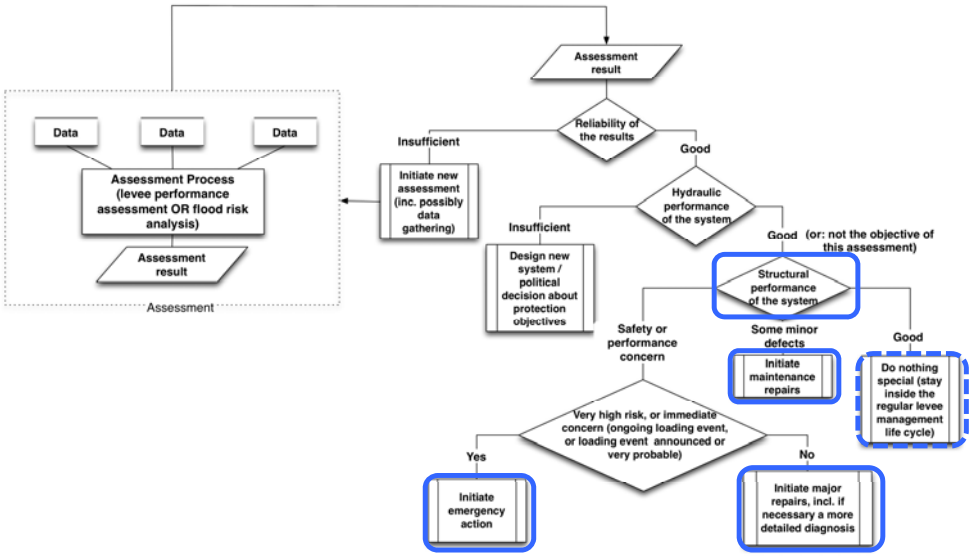
Receptor

Levee system risk analysis framework
Adapted from the ILH Fig. 5.7

Further reading:
ILH Chapter 5, sections 5.1 & 5.2

# Introduction : risk analysis and decision making

- Risk analysis potentially takes into accounts all factors influencing the overall risk, and allows to identify countermeasures:
  - structural changes
  - or security measures (ex: inspection and maintenance)
- Diagnosis of (potential) failure modes




Assessments, risk analysis and decision making
Adapted from the ILH Fig. 5.1

# Levee failure modes – Hydraulic vs. structural

- **Levee system failure**:
  flooding of the protected area before the nominal protection level is reached (= hydraulic/functional failure)

- **Levee failure** (structural):
  deterioration/damage/**breach**

- From the ILH (3.5.1.1):
  - Hydraulic failure (non-structural) occurs if water ingress into the leveed area (by through-flow, overflow or overtopping of the levee) occurs before the planned protection level is reached and without prior damage to the system element
  - Structural failure occurs by a breach in the levee system that results from damages affecting at least one system segment.
  - Structural failure can induce hydraulic failure and vice versa

# Levee failure modes – Scenarios

- (Structural) failure of a levee is (very) often the result of multiple deterioration/damage mechanisms involving one or more different components of the levee supporting each one or more function

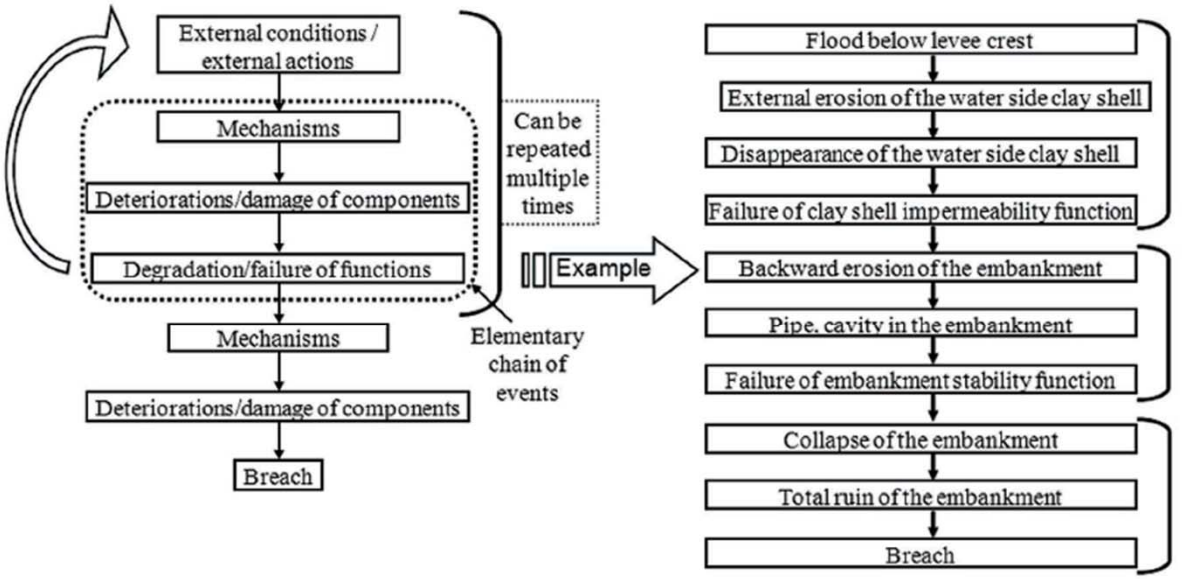



*Figure 3.166 Scenario or chain of events leading to a structural levee failure and breach (courtesy R Tourment, Irstea)*

# Levee failure modes – Failure modes analysis

- (potential) Failure Modes Analysis determines which scenarios may occur or have occurred. It is an almost essential step of a risk analysis
- Different methods exist to conduct a FMA, we (Irstea) propose a method for embankment levees based on functional analysis where some generic functions have been defined:
  - Stability
  - Impermeability
  - Filtration
  - Self-filtration
  - Drainage
  - Protection (against external erosion)
- From the material scale (mechanism) to the structural scale (breach)

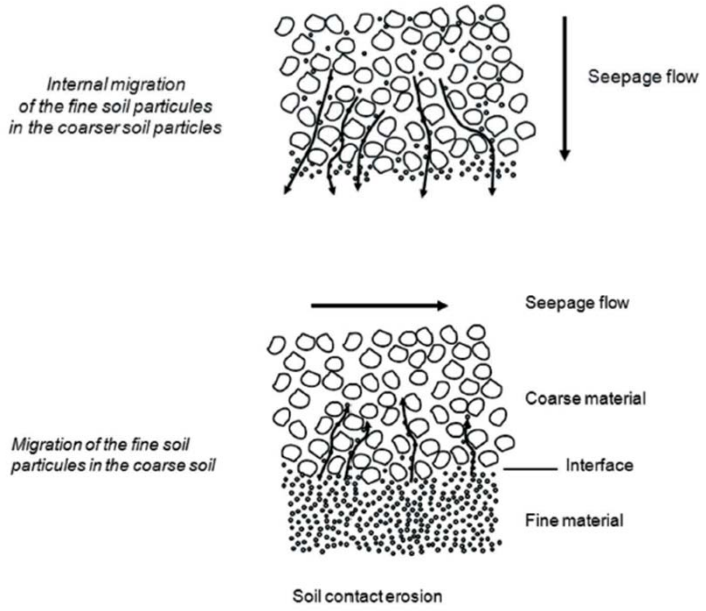
# Internal erosion mechanisms in failure scenarios

- How can the different mechanisms of internal erosion can lead to other mechanisms (of internal erosion but also others)? (See next slides)
- The European FP7 research project FloodProBE (action 3.1.1) took a look at internal erosion mechanisms and how they can interact

- To put it schematically, the different IE mechanisms can occur simultaneously in a levee in different places or successively in the same place

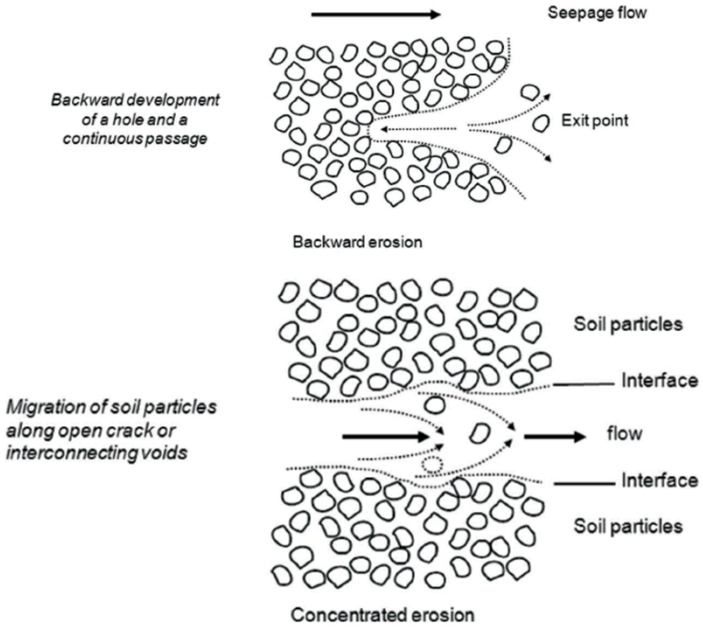
# Internal erosion mechanisms in failure scenarios

- The different mechanisms and some possible consequences:
  - Suffusion
    - Loss of resistance of the soil: settlement, sinkhole, internal regressive erosion, clogging of downstream filter
  - Contact erosion
    - Creation of a “conduit”: settlement, collapse, concentrated leak erosion



# Internal erosion mechanisms in failure scenarios

- The different mechanisms and some possible consequences:
  - (Internal) Backward/regressive erosion
    - Creation of a “conduit”: settlement, collapse, concentrated leak erosion
  - Concentrated leak erosion
    - collapse
    - usually one of the last mechanisms before breach / failure
  - All IE mechanisms:
    - augmentation of seepage and by consequence any mechanism of internal erosion (upstream or downstream)



# Internal erosion mechanisms in failure scenarios

- Example of failure scenarios involving internal erosion and other mechanisms (external erosion / instabilities)
  - Other mechanisms before IE
    - External erosion of an upstream impermeable layer (then possibly any internal erosion mechanisms)
    - Cracking or liquefaction of a downstream impermeable layer (then internal regressive erosion)
  - Other mechanisms after IE
    - Settlement then external erosion by overtopping/overflowing

# Internal erosion mechanisms in failure scenarios

- The FloodProBE “matrix”

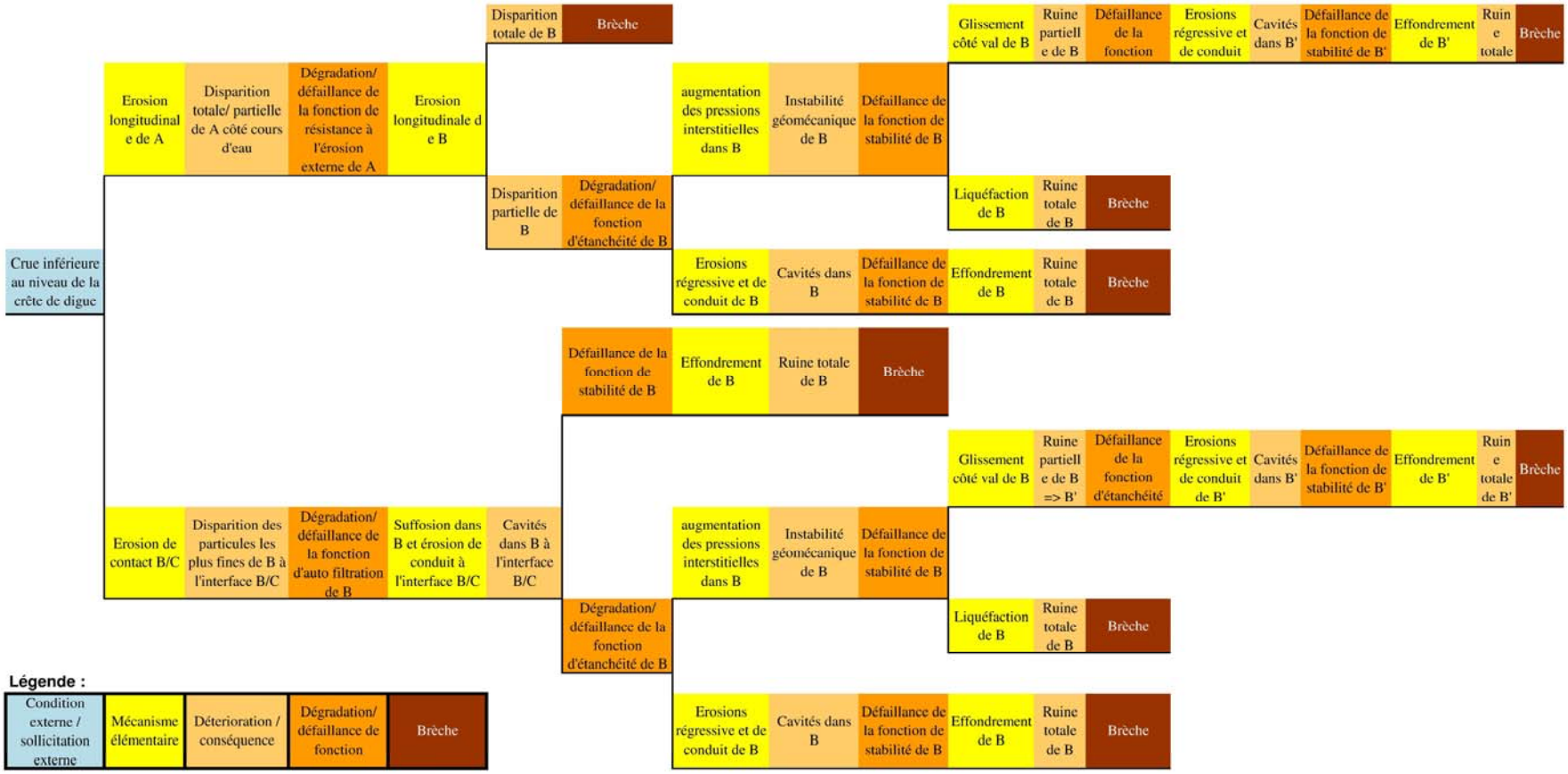
Table 2.3 Matrix of the main scenarios of embankment failure by internal erosion

| Type of internal erosion | Initiation | Continuation | Progression | Failure |
|---|---|---|---|---|
| Backward erosion | Uplift (at toe)<br>Local defect (hole, root)<br>Induced concentrated leakage (suffusion, contact | Beginning of pipe extension (parallel to flow) | Acceleration of pipe extension | Roof collapse<br>Sinkholes |
| | | | → Concentrated leak erosion | |
| Suffusion | Self-filtering condition not fulfilled | Without filter downstream | Yes | Settlement, Sinkholes |
| | | | → Backward erosion | |
| | | | → Contact erosion | |
| | | With filter downstream | Clogging, pore pressure increase | Diffuse instability (liquefaction) |
| Contact erosion | Tangential flow erosion | Cavities settlements (locally) | → Concentrated leak erosion | |
| | | | → Backward (or forward) erosion | |
| Concentrated leak erosion | Pre-existing opening (settlement, structure transition, layering)<br>Induced opening (contact erosion, settlement, backward erosion) | Beginning of pipe enlargement (normal to flow | Acceleration of pipe enlargement | Roof collapse<br>Sinkholes |

# How to use Bulletin 164 in practice in a risk analysis

- Estimation of failure probability
  - Knowledge on the different mechanisms and evaluation of their occurrence allows to assess probability of steps of the failure scenarios
- Barriers : filters and auto-filtration
  - Once the different scenarios are identified and assessed it is possible to identify barriers (or counter measures) to stop (or limit) scenarios
- Graphic representation of scenarios (trees) can help

# Use of scenario / event tree for assessment of failure probability



# Conclusion and perspectives

- Interest for the researchers in geomechanics to understand the use of these complex failure modes
- Initiation / continuation / progression / breach is a valid model but it can be improved / made more general by
  - involving more steps
  - and by making a distinction between actions, mechanisms, failure of components' functions
- Interest for engineers in charge of structural assessment or risk analysis to acknowledge the existence of different internal erosion mechanisms and their possible interaction, also in interaction with other mechanisms

# Conclusion and perspectives

- Within TC201 we would like to produce a document which makes an inventory of the different failure paths for the different failure mechanisms and makes a start on how residual strength could be assessed and taken in taken into account when establishing the safety of existing dikes or dike design. This document could be considered as an addition to the international levee handbook, ILH.
- The writing of this document is due for 2020. So, we have the possibility to introduce it during the ICSMGE in Sydney in 2021, in which we intend to organize a workshop and / or a session. If you are interested to join this initiative or if you have further questions, please contact by e-mail TC201 chair: cor.zwanenburg@deltares.nl.

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