

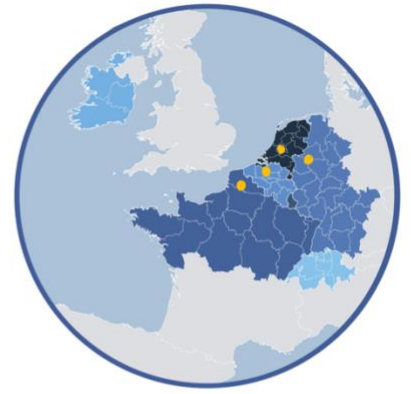
**Interreg**



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North-West Europe

Bonsai



# D.2.1.2 Jointly developed test plan on short-term robustness



**Climate and  
environment**

## D.2.1.2 Jointly developed test plan on short-term robustness



**Version:**

Final

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## Table of contents

<b>INTERREG NWE BONSAI project</b>	<b>6</b>
Climate change	6
BONSAI objective	6
Main results	6
BONSAI aims	6
Unique approach	6
<b>1 Introduction</b>	<b>7</b>
1.1 Overall operational objectives of the work on short term robustness	10
1.2 Foreseen results	11
<b>2 Meegroei-dijk</b>	<b>13</b>
2.1 General description of the pilot site and tests	13
2.2 Aim and site suitability	15
2.3 Contribution to overall objective	15
2.4 Link with other pilot activities	15
2.5 Description of survey performed. (Link to the test and reference site characterization)	16
2.6 Test protocol	17
2.6.1 Methods of covering the dike	17
2.6.2 Grass pulling tests	18
2.6.3 Monitoring vegetation development	19
2.6.4 Impact on drought	19
<b>3 Vlassenbroek</b>	<b>20</b>
3.1 General description of the pilot site tests	20
3.2 Aim and site suitability	22
3.3 Contribution to overall objective	22
3.4 Link with other pilot actions	23
3.5 Description of survey performed.	24
3.5.1 Lime treated cover layer	24
3.5.2 In-situ overflow tests	24
3.6 Test protocol	25
3.6.1 Wave impact tests:	25
3.6.2 Extraction of soil samples	26
3.6.3 Grass pulling tests	26
3.6.4 In-situ overflow tests	27
<b>4 Experimentation by Cerema</b>	<b>29</b>
4.1 General description of the pilot site and tests	29
4.2 Aim and site suitability	30
4.3 Contribution to overall objective	30
4.4 Link with other pilot actions	30

4.5	Description of survey performed. (Link to the test and reference site characterization)	30
4.6	Detailed description of the test protocol being executed	31
4.7	Test protocol	33
<b>5</b>	<b>Erodimeter</b>	<b>35</b>
5.1	General description of test equipment	35
5.2	Aim of the tests (Objective behind the development of the erodimeter)	35
5.3	Contribution to overall objective	36
5.4	Link with other pilot actions	37
5.5	Test protocol	38
<b>6</b>	<b>Tests UCLouvain and KU Leuven</b>	<b>40</b>
6.1	General description of test equipment	40
6.1.1	Geometry of the setup	41
6.1.2	Measurement techniques	42
6.1.2.1	Hydraulic Measurements:	42
6.1.2.2	Erosion Monitoring:	42
6.1.3	Soil sampling	42
6.2	Aim and site suitability	42
6.3	Contribution to overall objective	42
6.4	Link with other pilot actions	43
	<b>References</b>	<b>44</b>
<b>7</b>	<b>Introduction</b>	<b>46</b>
7.1	Problem description	46
7.2	Positioning BONSAI within ongoing initiatives	46
<b>8</b>	<b>BONSAI Activity A2.3 - Joint pilot action on animal Activity</b>	<b>48</b>
8.1	Scope and deliverables	48
8.2	State of the art and key knowledge gaps relevant to A2.3 deliverables	48
8.2.1	Current knowledge and practice	48
8.2.2	Burrow geometry, digging capacity and damage characteristics (D2.3.2)	49
8.2.3	Drivers of animal behaviour on levees (D2.3.3)	49
8.2.4	Sensitivity and vulnerability of levees to animal activity (D2.3.4)	49
8.2.5	Risk assessment and failure probability related to animal burrows (D2.3.5)	50
8.3	Synthesis	50
<b>9</b>	<b>Global rationale and activity structure</b>	<b>51</b>
9.1	Field campaigns	51
9.2	Expert judgement elicitation sessions	51
9.3	Desk research	51
<b>10</b>	<b>Rationale, objectives and key actions per deliverable</b>	<b>53</b>
10.1	Inspection, detection and monitoring methods for animal activity (D2.3.1)	53

10.2	Digging capacity and damage characteristics per animal and climate zone (D2.3.2)	53
10.3	Evaluation of animal behaviour relevant to levee safety (D2.3.3)	53
10.4	Classification system for sensitivity of levees to animal effects (D2.3.4)	54
10.5	Risk profiling and assessment framework for animal effects on levees (D2.3.5)	54
<b>11</b>	<b>Overview of field campaigns and test locations</b>	<b>55</b>
11.1	Field campaigns supporting D2.3.1, D2.3.2 and D2.3.3	55
11.1.1	Fort Everdingen (NL) – Beaver	55
11.1.2	Zwolle and Oijen (NL) – Beaver	55
11.1.3	Dijle (BE) – Beaver	55
11.1.4	Doeldijk (BE) – Fox and rabbit	56
11.1.5	Vught (NL) – Beaver	56
11.1.6	Zeeland (NL) – Mole	56
11.1.7	Additional and prospective locations	56
11.2	Field campaigns supporting D2.3.5	56
11.2.1	Marnewaard, Paddepoel and Flood Proof Holland (NL)	56
<b>12</b>	<b>Planning of actions</b>	<b>58</b>
12.1	Global planning of activity A2.3 (Q1 2025 – Q3 2028)	58
12.2	Indicative planning of field campaigns (Q1 2025 – Q3 2028)	58
12.3	Indicative planning of expert judgement elicitation sessions (Q1 2025 – Q3 2028)	58
<b>13</b>	<b>Organisation and coordination</b>	<b>59</b>

# INTERREG NWE BONSAI project

## Climate change

Climate change is accelerating, leading to increased rainfall, drought, storms, flooding, and sea level rise, particularly impacting the NWE region with its extensive estuarine systems. How can we better prepare these areas for climate change for the long term?

## BONSAI objective

The overall objective of BONSAI is to make flood defence systems in tidal estuaries of NWE more short and long term resilient against climate change by learning from sites in different climate zones over Europe and developing and sharing pro-active and responsive measures. Organisations responsible for flood resilience and societal partners in tidal estuaries in NWE are empowered through capacity building to strengthen their resilience and better act in case of flood threats caused by extreme weather events.

## Main results

The main results are (1) a transnational strategy for national authorities and 3 action plans for regional and local authorities, (2) 5 solutions on increasing robustness and resilience and enhancing disaster management and (3) multiple training schemes and courses on flood disaster management and flood resilience and 1 joint transnational flood academy.

## BONSAI aims

BONSAI aims to apply a holistic approach that is focusing on (short and long term) flood defence system resilience and the improved disaster management. Different NWE countries tackle these challenges from their own perspective. Transnational cooperation between the NWE regions and beyond is essential because estuarine systems and climate change transcend borders, offering opportunities for mutual learning and resilience building.

## Unique approach

The BONSAI approach is unique, 1. bridging the three layers of the multi-layer water safety approach: prevention, disaster management, and spatial planning 2. simulating shifting climate zones based on the application of insights from more southern regions to northern regions and 3. focusing on increased cooperation between countries to learn from each other, north learning from south as well as south learning from north.

## Test plans embedded in BONSAI

Within the BONSAI project in the second project period, Activity 2.1: Jointly Develop Test Plans for Pilots were planned. In this introduction, these test plans are put into context of the whole BONSAI project. The test plans are part of Work Package 2, pilots leading to solutions.

Following the NWE programme priority specific objective and the BONSAI project overall objective, three Project Specific Objectives (PSO) were formulated. For WP2 the project specific objective is the following:

1. Jointly develop and validate transnationally:
  - a. 2 short term flood defence robustness solutions
  - b. 2 long term increased resilience of flood defence systems solutions
  - c. And 1 solution for enhancing disaster management for flood risk related disasters
2. Towards the end of the project, the solutions will be fully implemented by our 6 flood risk management project partners and available for other authorities responsible for flood risk management.

For project period 2 (P2), Activity 2.1 of the project work plan focuses on jointly formulating Test Plans for pilot actions yielding the following three deliverables:

- D.2.1.2: Jointly develop a test plan on short term robustness
- D.2.1.3: Jointly develop a test plan on long term resilience
- D.2.1.4: Jointly develop a test plan on disaster management

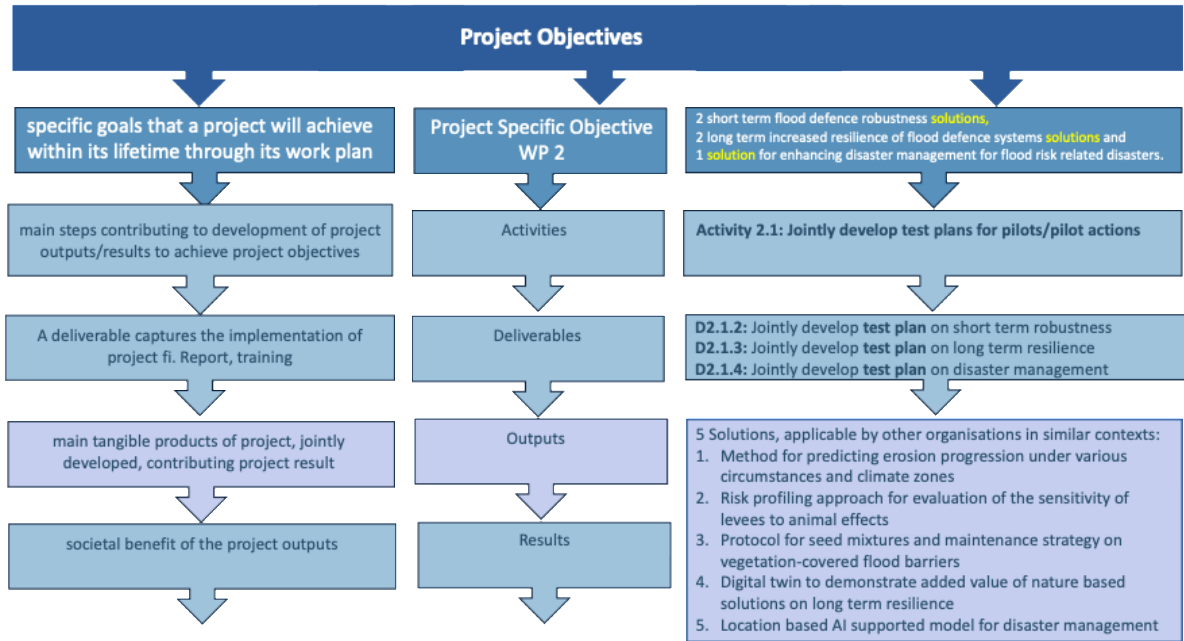
From the project organisational point of view, test plans are the foundation for achieving the PSO of WP2 and therefore the activities following A2.1 from P3 and further, being:

- Activity 2.2: Jointly implement pilot action for short term flood defence robustness – erosion
- Activity 2.3: Jointly implement pilot action for short term robustness – animal activity
- Activity 2.4: Jointly implement pilot action for long term resilience – biodiversity/vegetation
- Activity 2.5: Jointly implement pilot action for long term resilience – nature based solutions
- Activity 2.6: Jointly implement pilot actions for disaster management

These activities and their deliverables are envisioned to yield the following Outputs, namely 5 Solutions, applicable by other organisations in similar contexts:

1. Method for predicting erosion progression under various circumstances and climate zones;
2. Risk profiling approach for evaluation of the sensitivity of levees to animal effects;
3. Protocol for seed mixtures and maintenance strategy on vegetation-covered flood barriers;
4. Digital twin to demonstrate added value of nature-based solutions on long term resilience;
5. Location based AI supported model for disaster management.

Underneath a summarising figure is enclosed.



This test plan, on short term robustness, focuses on erosion and animal activities whilst incorporating relevant pilot actions of follow up activities A.2.2 and A.2.3.

# PART 1 – Erosion

## Introduction Activity 2.2: Erosion

Besides an increase in mean sea level rise, climate change creates the potential for more high energy storms and extreme weather events, thereby increasing the probability of extreme loading conditions for levees. BONSAI aims to help areas in North-West Europe prepare for climate change in the long term. The BONSAI approach thereby applies a multi-layer defence approach covering different topics. This specific document focuses on the topic of short-term robustness with a specific focus on erosion.

The strategic objective of BONSAI to promote climate change adaptation and risk prevention via the tactical objectives:

- Learn from different climate zones
- Develop pro-active response measures on climate change
- Develop solutions on short term robustness

The sections below describe briefly how these tactical objectives have been translated into operational objectives of the running brigade on short term robustness.

### Overall operational objectives of the work on short term robustness

Pilot actions within BONSAI are performed based on test plans. The pilot actions focus on increasing the strength of flood defence systems against erosion. This is mainly achieved via finding means to quantify and interpret the level of robustness. For work package 2.2. the deliverables as stated in the project proposal are:

**D.2.2.1:** Development of an erodimeter

**D.2.2.2:** Report of the impact of different weather and climate circumstances on erosion resistance

**D.2.2.3:** Report on the influence of drought on the erosion resistance of soils

**D.2.2.4:** Report on the influence of shrinking cracks on the erosion resistance of levee cover layers

**D.2.2.5:** Database of erosion experiments on levee cover layer on different test sites

**D.2.2.6:** Evaluation report on pilot action erosion

**D.2.2.7:** Method for predicting erosion and erosion progression under various circumstances and climate zones.

In order to identify the impact of drought, extreme weather or shrinking cracks on the erosion resistance of soil, first it is necessary to uniformly define the erosion resistance of soils and how to quantify, monitor, and interpret this. Consequently deliverables D2.2.3, D2.2.4 and D2.2.5 first require the development of:

- a validated method for determining the effects of extreme weather, drought and shrinking cracks to facilitate a long-term monitoring programme,
- a framework to be able to interpret the outcomes of the test methods in a common way such that the results obtained by one partner are correctly interpreted by other partner working on this topic. This is a key ingredient for knowledge transfer

- a framework to determine the relative significance of an impact in comparison to uncertainties in de load prediction or the accuracy within which the erosion resistance can be defined.

The development of these methods and frameworks require an evaluation and validation of the current state-of-the-art methods for assessing the erosion resistance of soils. Within BONSAI a combination of small sized, medium sized, and prototype scale testing will be used to achieve this.

Prototype scale testing provides a lot of insights into the physical behaviour of levees under extreme loads. However, the costs of prototype-scale tests make them unsuitable for monitoring changes in erosion behaviour and for determining spatial variabilities herein. Instead, this requires simple monitoring tools of small or medium size. These simple tools should however provide a reliable prediction of the erosion characteristics of the soil, also found during prototype scale tests. In line with aiming to achieve the 7 deliverables the running brigade on erosion first aims to determine a good and reliable way of interpreting the outcomes of erosion tests such that an optimum is found in the correlation between the small/medium sized test results and the results of strength and erosion tests at prototype scale. A work plan has been developed by the running brigade erosion to describe how to achieve this first step and how this feeds into the ability to reach the other objectives.

When it is deemed possible to correctly predict the erosion characteristics of soil and to monitor the changes herein, the methodology for predicting the erosion characteristics will be outlined and combined with a prescribed means of modelling erosion progression in levees and dams due to wave overtopping or overflow. This last action builds upon the work already performed within the EU Interreg2Seas project Polder2C's on the development of the numerical Overtopping Erosion model. The results will be disseminated via Deliverable D.2.2.7.

The test plans in this section describe how they feed the development of the method and frameworks which in turn are used to achieve the deliverables.

### Foreseen results

Based on the foreseen analyses the following results are expected to come out of the 4 battalions which will feed the deliverables.

1. International agreements on how to evaluate the stresses and erosion parameters following from erosion tests such that an optimum calibration between the outcomes of erosion tests is achieved.
2. International agreement on how to account for the uncertainty in stress predictions and predictions of the erosion parameters for use in probabilistic modelling runs
  - Advice on how to monitor and evaluate the impact of shrinking cracks on the erosion parameters
  - Measure for the recovery and growth rate of original vegetation
3. Measure for relating the erosion resistance against the pull-out resistance of grass

- Means of uniformly interpreting the outcomes of profile pit inspection results and how this related to the erosion resistance for use in erosion models
- An erosion model based on the same principles of interpreting the erosion resistance.

# Meegroeidijk

## General description of the pilot site and tests

The principle of the Meegroeidijk is that the dike is enlarged by overlaying it with sludge, see Figure 1. The main goals are to follow the sea level rise or compensate the soil subsidence.

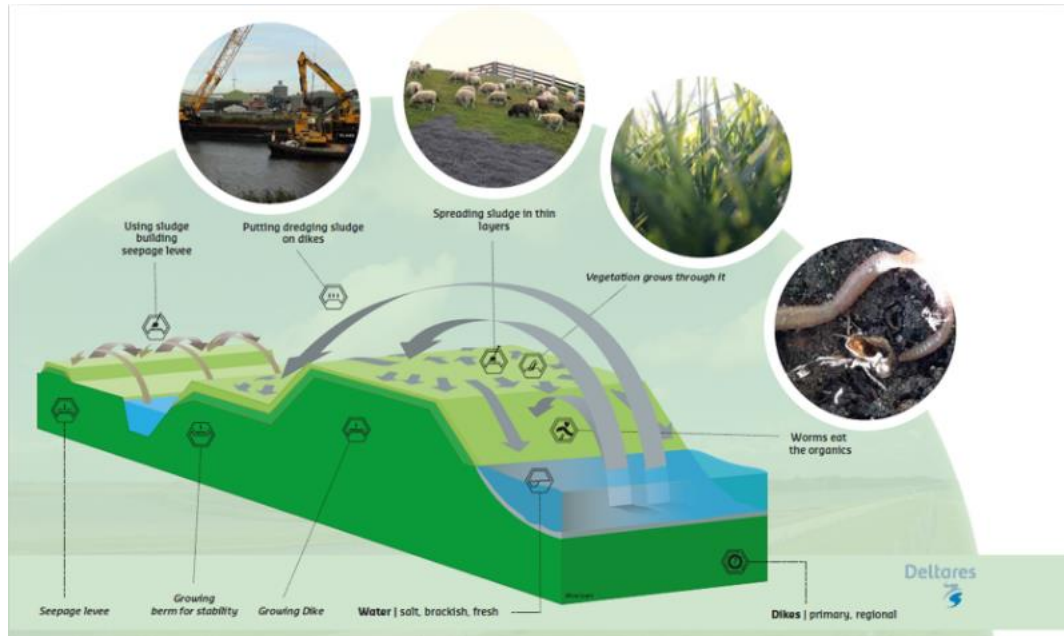


Figure 1 The principle of the Meegroeidijk

The aspect of the Meegroeidijk is being tested on three different locations. These were selected for their diversity, to optimize knowledge development and to ensure maximum applicability to (Dutch) flood defenses. The pilots differ in:

- Types of soil (Saline clay-rich silt vs potentially, fresh organic silt from rivers and waterways);
- Geometry;
- Vegetation; Location and subsoil conditions

The first location is situated at the Westpolder in the North-Western part of Groningen in the Netherlands. This is seadike which is still in function, see Figure 1. At this location salt sludge is placed on the dike. This will be done for several years. The pilot site is divided in several plots. They differ in the thickness of the layer and if a seed mixture is added to the sludge or not. For this, two mixtures have been selected.

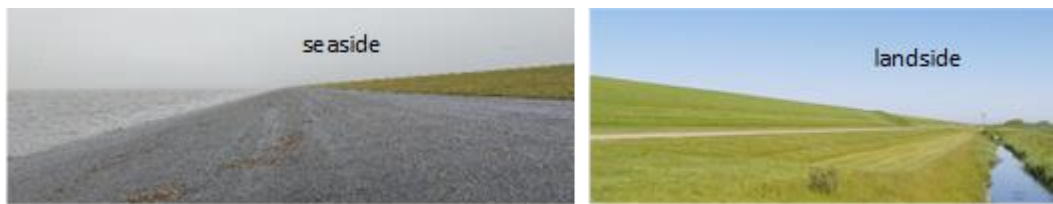


Figure 2 seadike Westpolder at the Groningen northcoast

Another pilot site is located more in the Western part of the Netherlands approximately 5 kilometers North-East of Alphen aan de Rijn (coordinates: 52°16'00.57"N, 4°70'08.09"E), see Figure 2. This dike is situated in a peat meadow area and is mostly build up from peat itself which makes it vulnerable for long dry periods. At this location fresh water sludge will be deposited with a rather high organic matter. One of the specific aspects which will be determined is the impact on the humidity of the dike. For this moisture sensors will be placed in the different plots where either sludge is being or not being deposited.



Figure 3 local dike near Alphen aan de Rijn

The third pilot site is situated near the wastewater purification system Nieuweer (coördinates 51°63'12.9 "N 4°70'80.6 "E) which is located about 10 km north of Breda in the Netherlands, see Figure 3. At this location trenches have been filled with sludge combined with several grass seed mixtures which differ from composition. By this means a prefab grass revetment will be produced. The final goal is to find out which combination of sludge and seed mixture results in the best grass/vegetation revetment.



Figure 4 Test location wastewater purification system Nieuwveer

### Aim and site suitability

The aim in the content of short-term robustness is to gather knowledge on the effect of sludge being put on top of the grass revetment of a dike. Will it die or reveal itself? Does this depend on the type of sludge and/or the thickness of the layer? To get answers to these questions several aspects will be taken into account such as fresh- or saltwater sludge, the organic matter content and the thickness of the layer of sludge placed on the dike. During the project regularly information on the development of the vegetation is gathered and analysed. Also the weather conditions are monitored. At the end of the project the strength of the erosion resistance of the vegetation will be tested with grass pulling test.

The pilot site at the Westpolder can be visited by public all year round. Many people travel along by bike. Especially at this pilot site a billboard will be placed to give more information about the project. The other pilot sites are situated on private property and cannot be visited every day. For these sites, fieldtrips can be organized.

### Contribution to overall objective

By testing the effect of sludge with different characteristics and difference in layers knowledge is developed on the impact of oversurfacing a dike with sludge (see Figure 1)

Within the scope of BONSAI a special seed mixture, which resulted from the project Future Dikes, can be tested in the Netherlands and at the site of CEREMA. The Future Dikes project aims to develop new climate robust and flower rich seed mixtures to serve as erosion resistant levee covers. Also the seed mixture which is regularly being used in the Netherlands will be tested on this site. By comparing the development of the vegetation, the sustainability in relation to climate change can be determined.

### Link with other pilot activities

Grass pulling tests will be executed with the same instrument that is being used in Vlassenbroek. This will also be done as much as possible with the monitoring of the

development of the vegetation. By this results from the Meegroeidijk and Vlassenbroek can be compared. The

**Description of survey performed. (Link to the test and reference site characterization)**

In 2022 the possibility to use sludge from the harbour of Lauwersoog for the principle of Meegroeidijk has been tested with small and medium scale experiments, see Figure 5. One of the questions to be answered was how quick the sludge would dry out and how much would remain of the original thickness. This test was followed up by an experiment at the pilot site Westpolder where in 2023 sludge was being sprayed against the dike, see Figure 6. This was done in layers of 2 cm's respectively 5 cm's. At some plots the normally used D1 seed mixture was added. Sometimes the sludge was prewashed with fresh water, see Figure 7. The vegetation survived well but there was hardly any difference found in the remaining thickness of the layers<sup>1</sup>.



Figure 5 Small scale and medium scale tests



Figure 6 Spraying sludge and its result at the Westpolder in 2023

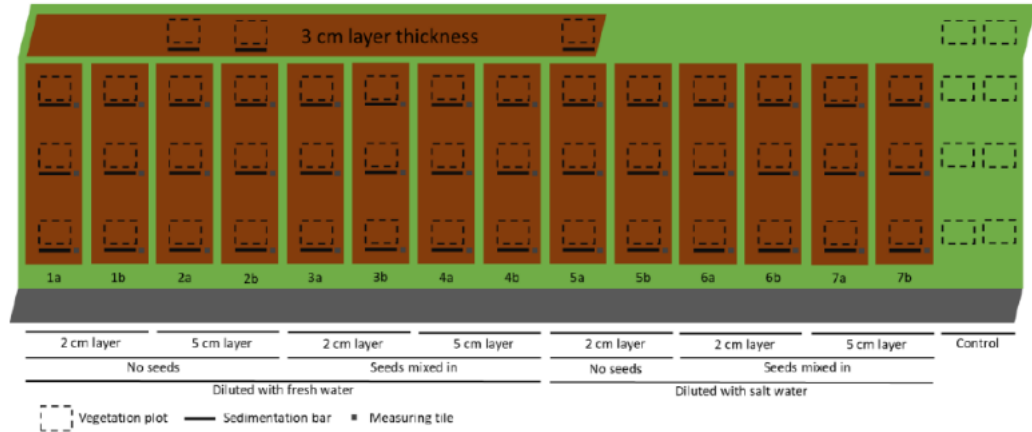


Figure 7 Overview of testplots

### Test protocol

#### Methods of covering the dike

At the pilot site Westpolder, the means to cover the dike with saltwater sludge has been tested in September 2025. For this sludge was being dredged from the harbour of Lauwersoog and transported to the dike. Finally a manure injector was used to cover the dike. The aim behind this method was to get a layer that would be of the same thickness all over the slope or the crest of the dike, see Figure 4 and Figure 5. This will also be done in 2026 and optionally in 2027.



Figure 8 the usage of the manure injector to cover the dike



Figure 9 The results of covering the dike with saltwater sludge

At the pilot site nearby Alphen aan de Rijn the impact of overlaying the dike will be tested in a different way. At this location sludge is brought on top of the dike straight from the neighbouring waterway. This will only be done in 2026 and in much thicker layers of approximately 10 cm and 20 cm.

#### Grass pulling tests

The maximum allowable tensile force on the grass cover can be assessed using a turf puller, see Figure 4. For the execution of the grass pulling tests four pins are anchored horizontally into the sod at 4 centimeters below the surface, to prevent the pins from tearing through the sod. To insert the pins into the sod, the soil is removed from at least two sides of the frame. When soil is removed at all sides of the grass sod, only the bottom of the sod offers resistance against the applied force. When the soil is only removed at two sides of the grass sod, the bottom and the two other sides provide resistance against the uplifting force. It is not possible to test the pull out resistance of a completely intact grass sod with this device. Nevertheless this value could be derived after analysing the results of the pull out tests with respectively 4 sides, or 2 sides cleared.



Figure 10 turf puller and 'results' of the test in the reference plot

At the pilot site Westpolder 40 tests have been done in the reference plot. In September 2027 this will be repeated. At that moment grass sod pulling tests will also be executed in several plots where the dike has been covered with sludge. This activity will also take place at the pilot

site near Alphen aan de Rijn. The aim is to do these as well at the pilot site Nieuwveer. This depends though on the development of the vegetation.

#### Monitoring vegetation development

At all three locations the development of the vegetation will be monitored yearly. This will be done by using an internal standard method so that the results can be compared with the measurements at the other BONSAI pilot sites. In September 2027 also a monitoring of the root density in the different test stretches will be executed.

#### Impact on drought

At the pilot site nearby Alphen aan de Rijn the impact of sludge on the humidity of the dike will be tested. For this moisture sensors will be placed in the different plots where either sludge is being or not being deposited. This will start in 2026. To be able the impact well local weather data will also be collected.

# Vlassenbroek

## General description of the pilot site tests

At Flood Control Area Vlassenbroek two test locations are present:

- Test section with lime treated cover layer (see also paragraph 3.6 in ref. [3], indicated with the red line in Figure 11 gure 11), on which different grass mixtures were applied as well as directly on the lime treated soil (test strips C, D, E and F in Figure 12) as after application of a topsoil layer (test strips B and G in Figure 12).

On this lime treated cover layer and on the reference sections (H-L) wave impact tests will be executed to investigate the resistance to wave impact of the cover layer with grass vegetation. The wave impact tests will be executed during a period of two weeks from half March 2026. During these tests damage of the cover layer due to the wave impact will be monitored. In addition, soil samples will be extracted for the execution of erosion resistance tests with the erodimeter and grass pulling tests will be executed for assessing the pulling resistance of grass. JET-erosion tests are executed for determining the erosion resistance of the cover layer.



Figure 11 Situation test locations in FCA Vlassenbroek

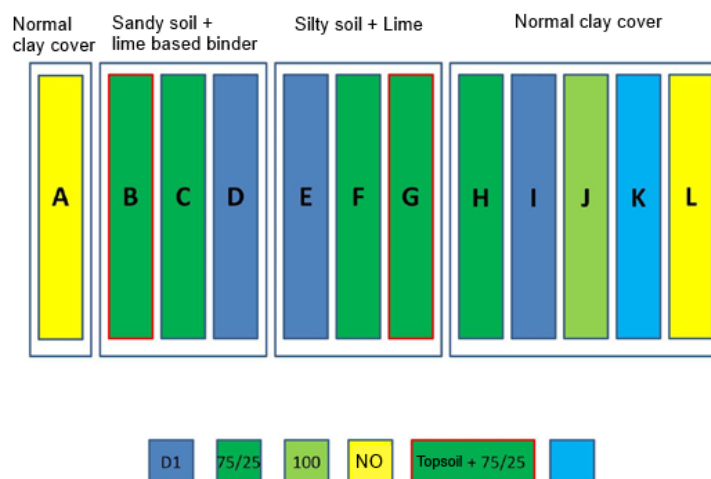


Figure 12 Different grass mixtures applied on the test strips with the lime treated cover layer

- Temporarily in-situ overflow test facility (see also paragraph 3.12.1 in ref. [3], indicated with the orange line in Figure 11): This facility, shown in Figure 13, allows for testing revetments suitable for overflow levees against design conditions.

The construction of the in-situ overflow test facility started in November 2025. During the first months of 2026 the first to be tested Open Stone Asphalt revetment with reduced permeability will be installed. Overflow tests will be executed during spring tide within the period March-June 2026. By end of 2025-beginning of 2026 an alternative study for the nature-based solution type revetment is carried out. The installation of this nature-based solution type revetment is aimed at autumn 2026 and the execution of overflow tests is aimed at winter 2027-2028. Only the revetment consisting of a nature-based solution is considered within the Bonsai project, the first tests with the Open Stone Asphalt revetment is executed outside the Bonsai-project, but additional hydraulic measurements can provide hydraulic boundary conditions for other pilot activities within the BONSAI-project (numerical modelling, medium scale physical model tests).

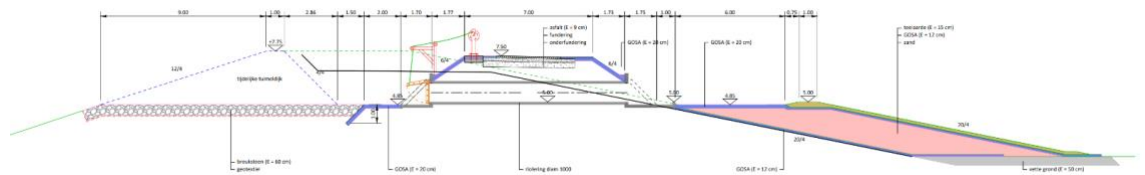


Figure 13 Cross section of the Temporarily in situ overflow test facility

### Aim and site suitability

Generally the test site of Vlassenbroek is most suitable for executing the different types of tests because of the presence of the test section with the lime treated cover layer, a reference section with the normal clay cover layer and the presence of different vegetation types on these cover layers. The main tests executed on the lime treated cover layer are the wave impact tests. For comparison with results of tests executed at other pilot sites within the BONSAI project or with results of tests executed at the reference sites of the BONSAI-project also JET-erosion tests and grass pulling tests are executed. Soil samples are also extracted for executing tests with the Erosion Function Apparatus (EFA-tests). For execution of the overflow tests a specific temporarily in-situ overflow facility will be built on the Scheldt levee of the Vlassenbroek inundation area.

The aim of the different tests executed is the following:

- Wave impact tests: this is a prototype-scale erosion tests aiming at assessing the erosion strength of the lime treated cover layer, and the erosion resistance of the clay of the reference sections.
- Grass pulling tests: this is a small sized tests for the assessment of the maximum allowable tensile force on the grass cover
- JET-erosion tests: This is a small sized erosion test to characterize the surface erosion resistance of the cover layer of the levee. From the JET-erosion tests erosion parameters as critical shear stress and a coefficient of erosion are derived. Another method to determine the critical shear stress of the cover layer is executing tests with an erodimeter (see Chapter 0)

The actual aim within the BONSAI project of the execution of these tests is to use the results for the execution of the comparison between prototype scale test methods and small-scale test methods. In addition, a comparison of results of these tests with the same tests executed at other pilot site locations and at reference sites is aimed at, e.g. wave impact tests and grass pulling tests are executed at Vlassenbroek and at the reference site of Falsterbö, critical shear stress derived from JET-erosion tests can be compared with the critical shear stress derived assessed with the erodimeter. Within BONSAI is also being investigated whether it is possible to relate the outcome of the erosion measurements due to wave impact with the outcomes of a Dutch research project on the erosion of clay.

During the overflow test on the OSA-revetment with reduced permeability, the opportunity exists for the execution of extra hydraulic measurements, which can serve as boundary conditions for both small scale as mid-scale experiments on levee cover layers or as validation for numerical modelling. The results of overflow tests can be compared with overflow tests executed at the levee at the Cerema test site.

### Contribution to overall objective

By using and comparing different methods to test the erodibility of a levee cover, approaches can be aligned to uniformly interpret the robustness of levee covers.

The results of the tests executed in Vlassenbroek, i.e. wave impact tests, JET-erosion tests and EFA-tests, can be compared with test results of tests executed at other pilot sites of reference sites, leading to comparison of the level of robustness from sites in different climate zones.

The tested cover layers concern a lime treated cover layer and a nature-based solution cover layer, which are possible solutions for the short-term robustness of levees.

#### **Link with other pilot actions**

The wave impact tests on the lime treated cover layer and the wave impact tests on the reference section with the normal cover layer can be compared with wave impact tests executed at the reference site in Falsterbö (Sweden).

The results of the grass pulling tests can be compared with results of grass pulling tests executed at e.g. the Meegroeidijk in the Netherlands.

At the test site with the lime treated cover layer soil samples will be extracted for executing tests with the erodimeter. The results of the tests with the erodimeter can be used in the comparison between large- and small-scale erosion tests, from which the results are used to identify a framework for levee cover erosion.

At the test site with the lime treated cover layer different types of vegetation are applied. Within the biodiversity theme in the BONSAI-project vegetation monitoring is executed and influence of climate change on vegetation on levees is assessed. The yearly vegetation monitoring as part of the regular monitoring of the lime treated test section can be used in the framework of the biodiversity theme of the BONSAI-project.

### Description of survey performed.

#### Lime treated cover layer

The regular monitoring of the lime treated cover layer (see also paragraph 3.11 in ref. [3]) consist of:

- Yearly a topographic survey using a drone is executed, including the generation of an orthophoto and a DTM of the test section
- Monitoring of the vegetation development: This implies a yearly monitoring of the vegetation coverage and biomass production. In 2022 and 2025 also a monitoring of the root density in the different test stretches is executed.
- JET-erosion tests: in 2020 and 2022 JET-erosion tests were executed to assess the erosion strength of the lime treated cover layer. In 2022 also four JET-erosion tests were executed in the reference section with the normal cover layer.
- In 2020 and 2021 the soil permeability was assessed by executing lab permeability tests on soil samples extracted from the field.

#### In-situ overflow tests

During the execution of the overflow tests geographical monitoring of the test section will be executed. Other measurements executed during the overflow tests are described in paragraph 0.

## Test protocol

### Wave impact tests:

At the test section with the lime treated cover layer and the reference cover layer, wave impact tests will be executed to investigate the resistance of the cover layer to wave impact. The wave impact test will be executed during a period of two weeks using the Wave Impact Generator (WIG). Since the duration of a wave impact test at one test section is estimated to take approximately two days, including switching between one test section and the following, during the two week period wave impact tests can be executed at 4 test sections. In consultation with INBO, executing the vegetation monitoring, test sections C, F, G, and H (see Figure 12) are proposed for wave impact tests during this two week period. If damage occurs more quickly on certain test sections or if the first tests conducted show that a shorter duration is possible for certain reasons, other test sections may also be considered within this two week period (e.g. test sections D and E in Figure 12).

The WIG has a volume of 1 m<sup>3</sup>, is two meters wide, and is equipped with a double drop gate. For these tests, the generator is suspended in the front loader of a mobile wheeled crane (see Figure 12). This allows the location of the wave impacts to be easily varied during the test. To prevent upward and downward movements of the WIG, it is fitted with height-adjustable, hinged support legs, moving along rails installed on both sides of the test section.

In the toe trench of the levee, a frequency-controlled electric submersible pump is installed. Water is pumped to the WIG through pipes. Since a filling flow rate of approximately 50 L/s is used during the tests a pump with a capacity of 200 m<sup>3</sup>/hour will be foreseen.

The WIG allows to a certain level to simulate natural wave fields. Every simulated wave impact represents a specific pressure depending on the fill height of the WIG. In order to reproduce the natural variation in impact location as accurately as possible, the impacts to be simulated are applied at three different positions within the test section, only 0.40 m (measured along the levee slope) apart from each other. At each position 20 impacts are simulated. After the last impact at the lowest position, the generator is moved back to the top position. Consequently, one cycle consists of 60 impacts. In principle, the same distribution is used as for the wave impact tests executed at the Hedwige- and ProsperPolder, i.e a wave height ( $H_{m0}$ ) of 0.65 m and a peak period ( $T_p$ ) of 2.89 s, resulting into a wave steepness of 0.05. One storm hour consists therefore of approximately 480 wave impacts, or 8 cycles.

Erosion of the grass cover and the lime treated cover layer is planned to be measured using the following methods:

- 3D scans of the damage of the grass cover and the cover layer are planned to be executed with an iPhone Pro and a specially developed app, using as well as photogrammetry as LIDAR measurements. Extra precision is added using RTK-GPS measurements.
- The University of Louvain-La-Neuve (UCLouvain), also partner within the BONSAI-project will measure the damage of the grass cover and the cover layer using photogrammetry.

#### Extraction of soil samples

In order to execute the tests with the erodimeter, the following soil samples will be extracted from the test section with the lime treated cover layer:

- 8 soil samples will be extracted from the test strips with the lime treated cover layer. For each of both types applied lime treatment, two samples will be extracted from a test strip with topsoil on top of the lime treated cover layer and two samples from a test strip with the grass directly sown on the lime treated cover layer. On the levee slope of each considered test strip one sample will be extracted near the crest and one near the toe of the levee. Considering the lime treated cover layer being very hard these samples will be extracted using a coring machine.
- 2 soil samples will be extract from a test strip within the reference section with the normal cover layer. On the levee slope of this test strip one sample will be extracted near the crest and one near the toe of the levee. These soil samples can be extracted using manual coring.

Also for the nature-based solution cover layer tested at the temporarily in-situ overflow facility soil samples will be extracted for the execution of tests with the erodimeter.

#### Grass pulling tests

The maximum allowable tensile force on the grass cover can be assessed using a turf puller (Figure 14)



Figure 14 Turf puller

For the execution of the grass pulling tests four pins are anchored horizontally into the sod at 4 centimeters below the surface, to prevent the pins from tearing through the sod. In order to insert the pins into the sod, the soil has to be removed from at least two sides of the frame (see left frame of Figure 15). When soil is removed at all sides of the grass sod, only the bottom of the sod will resist against the applied force. When the soil is only removed at two sides of the grass sod, the bottom and the two other sides will provide resistance against the uplifting force. Because of this, it is not possible to test the strength of an intact grass sod with this device.

The sod is lifted by a hydraulic cylinder which is manually operated with a steering wheel (see middle frame of Figure 15). This cylinder induces an increasing displacement on the grass sod, until the sod fails and is pulled out of the top layer (see right frame of Figure 15). During the tests the force and displacement are measured (and recorded), which are then used for the analysis of the strength of the grass sod. In order the derived strength of the grass sod to be statistically relevant (ref. [4]), at least 20 grass sod pulling tests must be executed at a certain test section.

Consequently 20 grass sod pulling tests will be executed at one test strip with top soil on top of the lime treated cover layer and 20 at a test strip with the reference cover layer.



Figure 15 Different stages during the sod pulling tests: Top view condition 4 (left); Test set-up (middle); Pulled out sod (right)

In-situ overflow tests

When the installation date of the first to be tested revetment is decided, the exact date for executing the in-situ overflow tests will be selected based on astronomical tide predictions of the river Scheldt near Vlassenbroek. A first analysis of the astronomical predicted water levels concludes that the relevant high water conditions occur at the end of each month in the period May 2026 to June 2026, see Figure 16

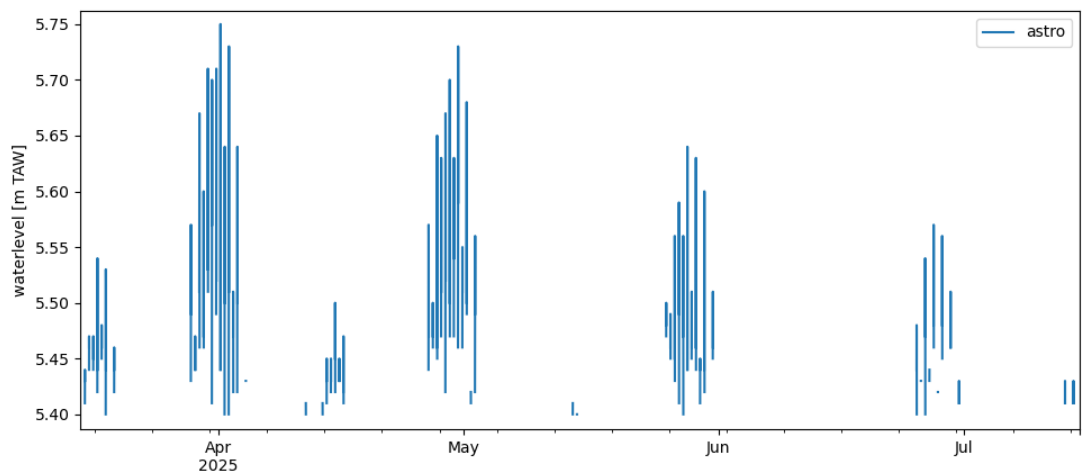


Figure 16 Astronomical predicted high waters at the river Scheldt near Vlassenbroek with an overtopping of the crest exceeding 0.40 m

The culverts are sealed by flap gates. Before an overflow test the gate will be opened and water is overflowing the to be tested cover layer. The aim is to continue the test until the water level in the Scheldt River descends again towards a level lower than the crest level. If needed the test can be stopped by closing the flap gates.

The measurement set-up is based on the experience gained during Interreg 2Seas project Poldr2C's. During the overflow tests following measurements will be executed:

- Water level at river side and water level within the flood control area.
- Discharge through the culvert. This discharge is calculated using a QH-relationship of the culvert, derived from a measurement of the discharge through the culvert and a measurement of the water level in the river Scheldt.
- Hydraulic grade line at the landward levee slope using a 2D-LiDAR line scan.
- Velocity on the landward levee slope using PTV or LSPIV processing of drone-based recordings of the overflowing water.
- Moisture and pressure in the underlying sand package.
- Deformation and erosion of the cover layer based on accurate 3D LiDAR scans.

# Experimentation by Cerema

## General description of the pilot site and tests

Cerema has a controlled experimental dike at the Experimentation and Research Centre of Cerema, in Rouen, which will constitute one the bases of our erosion experiments in France we will carry out in the near future in French test site of Caen to Ouistreham.

A schematic diagram of the dike is shown in Figure 17 and photos in Figure 18.

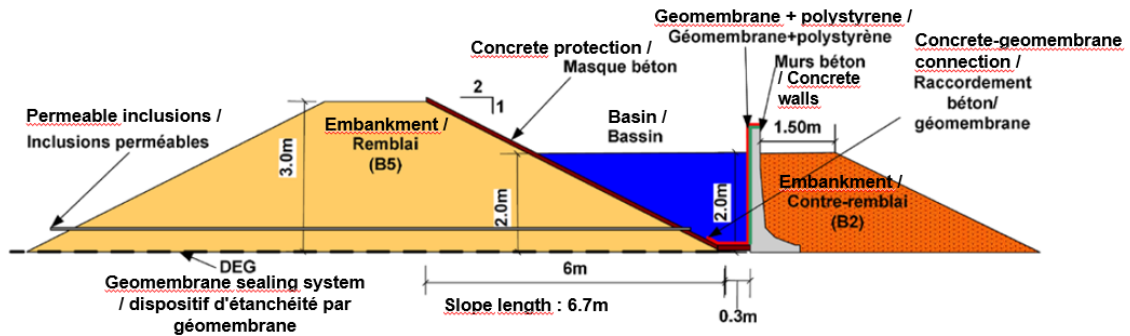


Figure 17: Scheme of the experimental pilot site Cerema (Vautrin *et al.*, 2024).



Figure 18: View of the experimental pilot sit Cerema

The dike is available for the BONSAI project from the 2<sup>nd</sup> half of 2026. For the purpose of the tests for BONSAI, it is planned to dismantle the concrete protection in order to carry out in-situ JET (Jet Erosion Test) and an overflowing test on the remaining dike slope consisting of sandy - silty soil.

Depending on its availability, it is also planned to carry out in-situ MojET (Mobile Jets Erosion Test) and EFA (Erosion Function Apparatus) tests, if Ø 75 mm coring on the slope of the embankment is possible. In addition, it is planned to grass over part of the slope in sandy-silty soil in order to carry out a test on the sandy-silty soil and on the grassed sandy-silty soil.

### Aim and site suitability

The objectives are:

- to compare different types of surface erosion tests on the dike ;
- to use erosion test parameters to model the opening of a breach by overtopping (using software such as WinDAM C or equivalent) ;
- to compare the information obtained from the modelling with the data measured during the overtopping test on the dike slope ;
- to assess the impact of grassing the dike slope on the erosion resistance caused by overflowing.

The advantages of an experimental dike on a Cerema site are:

- it is accessible, with logistical resources on site;
- it can be damaged without fear;
- The results will be the base of the future experiment we plan to carry out in the French test site of Caen, and particularly on the Renault-Truck plant location.

### Contribution to overall objective

The test programme is designed to provide at least a partial answer to the question of the overflowing resistance of a silty-sandy soil dike, covered or not.

It may be supplemented by other tests and/or other observations at other sites, in the bonsai test sites as well as in Caen to Ouistreham site.

### Link with other pilot actions

The test programme includes tests such as the in-situ JET and the overflowing test, which will be carried out at other pilot sites. The test results can therefore be compared between different sites.

The grassing of the dike slope could be carried out with a mixture of seeds that will be used on other pilot sites, in different environments. A comparison of the growth of the grass and its contribution in terms of erosion resistance could be envisaged.

### Description of survey performed. (Link to the test and reference site characterization)

The construction of this experimental dike has been monitored and documented. It has been subjected to a number of non-destructive measurements since its construction. This information can be summarised.

At present, the samples and tests planned will be associated to erosion tests realization in 2026 and 2027.

**Detailed description of the test protocol being executed**

The JET tests (Figure 19) are carried out (by Inrae), if possible in-situ, on the dike slope, with a jet pressure normally used on natural soils. They are used to measure:

- critical shear strength (hydraulic)  $\tau_c$  (kPa)
- erosion coefficient  $k_d$  ( $\text{cm}^3/\text{N}\cdot\text{s}$ )

If the in-situ JET is not available, core drilling will be led in the dike in order to carry out the laboratory tests.  $\tau_c$  and  $k_d$  parameters can be used in a model of breach opening by overflow (WinDAM C type).

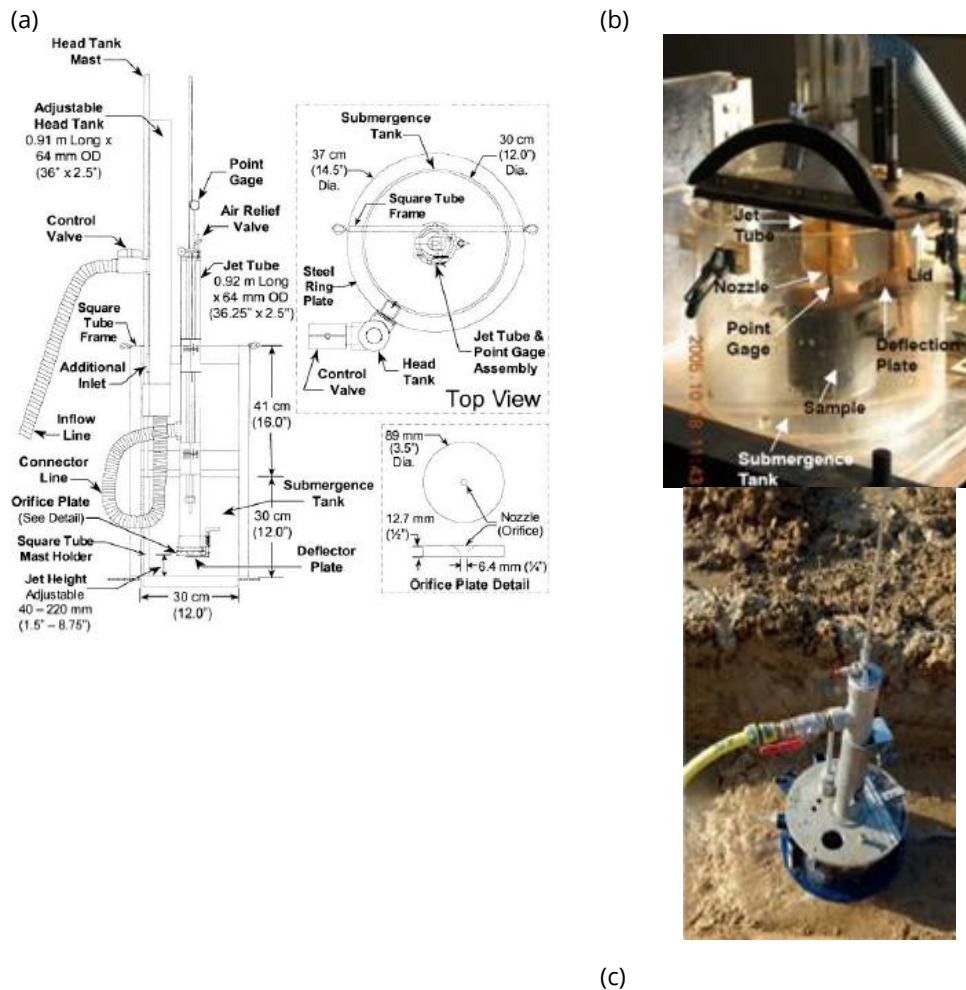


Figure 19: a) Hanson and Cook (2004) original apparatus (Nguyen, 2014), b) JET in laboratory (Hanson and Hunt, 2006), c) In-situ JET (Consortium DigueELITE, 2025)

MoJET tests (Figure 20, Figure 21) are carried out in situ (by Université Gustave Eiffel), on the dike slope, using a flow rate normally used on natural soils. They are used to measure:

- cumulative eroded mass (g)
- erosion rate (g/min)

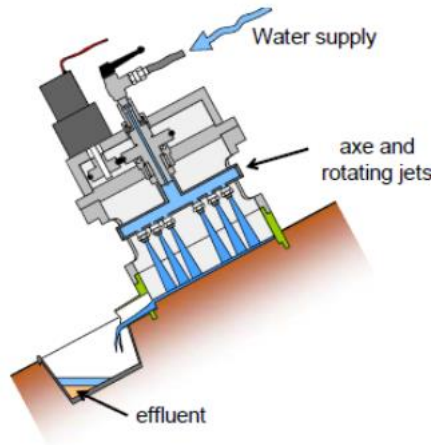


Figure 20: Mobile jets erosion (MoJET) test set-up: Schematic diagram of eroding unit (Haghighi, 2013)

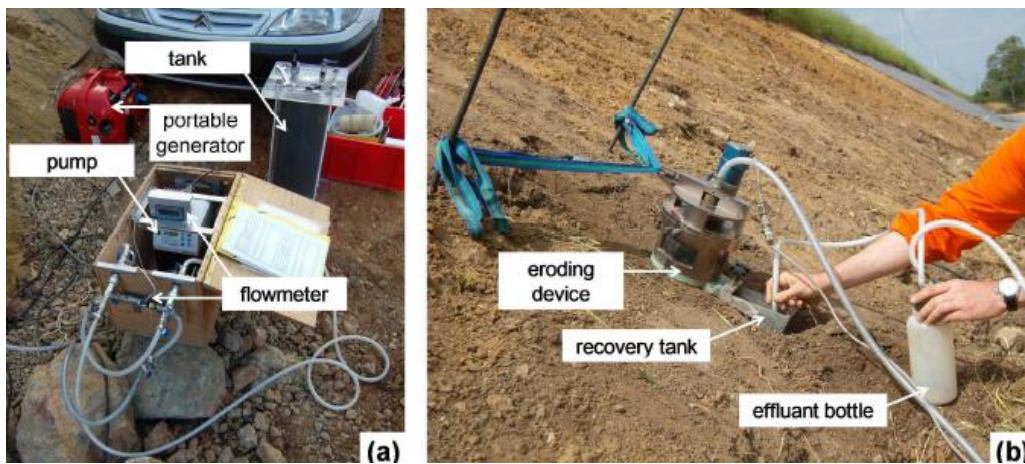


Figure 21: Erosion test in progress: (a) device and water supply. (b) Eroding system and effluent recovery (Haghighi, 2013)

EFA tests (Figure 21, Figure 22) are carried out in laboratory (by ESTP) on cylindrical samples 76 mm in diameter, taken from the dike. They are used to measure:

- velocity (m/s)
- shear stress (Pa)
- scour rate (mm/h)

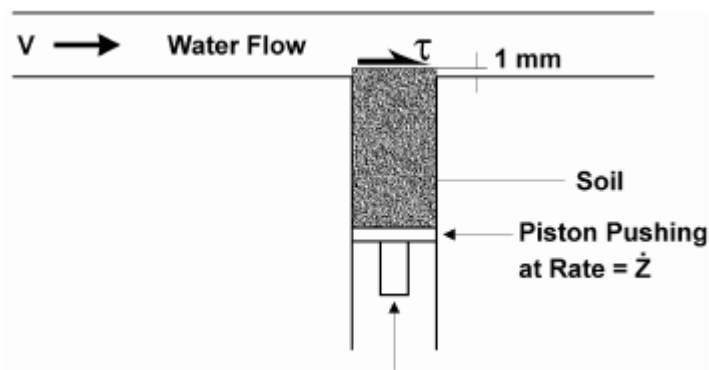


Figure 22: Schematic diagram of the Erosion Function Apparatus (EFA) (Briaud and Chen, 2005)

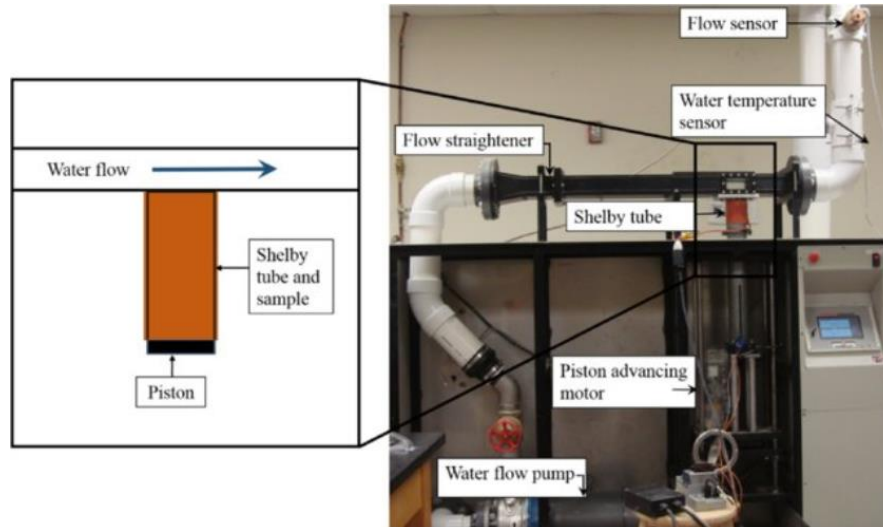


Figure 23: Example of EFA (Tixker-Kuleza *et al.*, 2017)

The overflowing test (Figure 24), measurement and monitoring methods will be discussed with Inrae (RECOVER team) during 2026.



Figure 24: Overflowing tests on DigueELITE experimental dike (Bonelli *et al.*, 2019)

### Test protocol

It is planned to carry out 2 cross-sections and 2 to 3 in-situ JET on the sandy-silty soil of the embankment. If possible, 4 in-situ MoJET and 4 cores  $\varnothing$  75 mm for laboratory EFA tests will also be scheduled. These tests could take place in the 2<sup>nd</sup> half of 2026. Then, the dike slope will be grassed over. Once the in-situ JET have been analysed, an overflow breach modelling will be carried out in the 2<sup>nd</sup> half of 2026.

2 overflow tests will be carried out on the embankment of the embankment in the 1<sup>st</sup> half of 2027, on the sandy-silty soil and on the grassed sandy-silty soil.

These tests will be carried out using a similar protocol to that used by Inrae on various demonstrators, including the DigueELITE project (Bonelli *et al.*, 2019):

- Standard reference: ASTM D6460
- Test carried out in a canal/channel:
- width: 61 cm
- length: crest + embankment slope + platform: 6.30 m
- slope: 3H/2V
- test duration: 30 min by flow rate; 1 complete test: 7 steps, 3h30
- initial flow rate: 95 l/s/m → final flow rate: 570 l/s/m
- 171 to 1 026 m<sup>3</sup>/m for 30 min (1 step of the complete test) + water consumption of +20 to +50% due to leaks in relation to the test channel
- water level in crest: 30 cm
- flow velocity at the bottom (dike toe): 5-7 m/s
- Topographical monitoring (laser, LiDAR, photogrammetry...), flow velocity measurement, etc.

The test, measurement and monitoring methods will be discussed with Inrae (RECOVER team) during 2026.

# Erodimeter

## General description of test equipment

Under the scope of the BONSAI project, ESTP is developing an innovative laboratory apparatus to measure soil erosion resulting from overflow and wave overtopping on hydraulic structures, such as dikes. The primary design objective is to achieve a high degree of physical similitude with natural processes, thereby ensuring reliable correlation between laboratory test results and in-situ performance.

The conceptual foundation of this device is the Erosion Function Apparatus (EFA), originally developed by J.L. Briaud in the 1990s [5]. This established methodology involves extracting soil samples from field sites and testing them under controlled laboratory conditions. In the standard EFA procedure, a thin-walled sampling tube (3 inches external diameter) is used to obtain a core sample at a specified depth. This sample is then positioned flush with the bottom of a testing channel. A water flow with a controlled, constant velocity (up to 8 m/s for the latest models) is directed over the exposed soil surface. The resulting hydraulic shear stress erodes the sample.

The apparatus currently under design and construction at ESTP will generate characteristic erosion function curves, plotting the erosion rate against the applied hydraulic shear stress. The erosion rate is defined as the ratio of the decrease in sample thickness to the duration of flow application.

## Aim of the tests (Objective behind the development of the erodimeter)

The development of this new erodimeter addresses a dual objective: to overcome the technical limitations of the current EFA through automation and better measurement equipment, and to provide a more versatile and representative testing platform through a modular and adaptable design capable of simulating a wider array of in-situ conditions.

### Context and Issues Identified with the EFA

The use of the Erosion Function Apparatus (EFA) has revealed some technical limitations. A primary issue is the determination of the erosion rate, which relies on visual assessment by the operator. This manual method introduces subjectivity, potentially leading to interpretation errors and compromised measurement accuracy.

Furthermore, the standard test method employs a small-diameter tube sampler (76 mm or 3 inches), resulting in a relatively small surface area exposed to water flow. This can make it difficult to correlate laboratory results effectively with data from in-situ tests. Additionally, this type of thin-walled tube, while common in the United States, is not widely used in Europe, creating challenges for standardizing practices.

Although methodological modifications have been proposed, particularly in some U.S. laboratories, these improvements remain partial and do not fully address the identified needs.

## Design Objectives for the New Erodimeter

The design of the new apparatus follows two main directions:

- **Improvements to Existing EFA Features:**

- Automation of Measurement: Implementation of an automatic system for measuring the erosion rate (or sample thickness variation), eliminating the subjectivity of visual inspection.
- Automatic Position Control: Integration of an automatic sample-adjustment mechanism to maintain the sample flush with the water flow surface throughout the test.
- **Innovations and Overall System Flexibility:**
- The new erosion meter aims for systemic improvement, requiring a novel design centered on greater flexibility:
- Sample Dimension Flexibility: The device will be designed to test samples of various sizes.
- Hydraulic Loading Flexibility: Capability to generate different flow types, specifically to simulate overflow or wave overtopping conditions. This will broaden the range of applications and improve the representativeness of tests for real-world scenarios.

### Contribution to overall objective

The erodimeter developed as part of the BONSAI project serves as an experimental tool for achieving two objectives: predicting erosion parameters and assessing the impact of climate change. Here is how its use is directly linked to these expected outcomes:

- **Link to predicting erosion parameters using simple tools**

The erodimeter bridges the gap between complex natural phenomena and usable engineering parameters.

- From Test to Key Parameter: The apparatus provides more than qualitative observation. It quantitatively generates the erosion function curve for a given soil, which is the relationship between the erosion rate (mm/h or mm/s) and the applied hydraulic shear stress (Pa). From this curve, a key erosion resistance parameter, such as the critical shear stress ( $\tau_c$ ) or an erodibility coefficient, can be directly extracted.
- Simplification for the Engineer: These quantitative parameters ( $\tau_c$ , erodibility coefficient) then become key input data for simple prediction tools used by engineers, such as semi-empirical formulas. Instead of modelling the complex physics of particle detachment, the end-user (e.g., a design office) can apply these laboratory-measured parameters directly to their structure stability calculations.
- The project's logical chain is therefore:

Field Sample → Erodimeter Test (in lab) → Derivation of Erosion Parameters ( $\tau_c$ , etc.) → Integration into Simplified Prediction Models/Tools → Support for the Design and Assessment of Hydraulic Structures.

The device's new flexibility (sample sizes, flow types) ensures that these parameters will be more representative of real-world overflow or overtopping conditions, thereby improving the reliability of the simple prediction tools that depend on them.

- **Link to assessing temporal changes due to climate change**

Climate change alters environmental loads (storm intensity/frequency, sea-level rise) but may also modify soil properties themselves (drought, freeze-thaw cycles, vegetation changes).

The erosion meter enables the direct assessment of how these changes affect a material's erosive response.

- Comparative assessment: The protocol allows testing soil samples of the same type - collected at different times or subjected to simulated climatic conditions - using the same reliable and reproducible method.
- Laboratory simulation: Samples can also undergo accelerated aging in the lab (e.g., wet-dry cycles, freeze-thaw cycles) that mimic the multi-year effects of climate change and then be tested immediately with the erodimeter.
- Measuring change: By comparing the erosion curves and derived parameters (e.g., the critical stress  $\tau_c$ ) before and after these climatic changes (real or simulated), the project will be able to:
  - Quantify the degradation (or, rarely, improvement) in erosion resistance.
  - Establish trends in how the erodibility of European dike soils is evolving in response to climate change.
  - Identify future vulnerabilities and prioritize sections of infrastructure requiring preventive reinforcement.

### Link with other pilot actions

#### Scientific Context and Challenge

Assessing the erodibility of soils in hydraulic structures (e.g., dikes, levees, embankments) exposed to external erosion hazards involves a wide array of testing devices and methodologies. A key research challenge is establishing reliable correlations not only between different laboratory apparatuses but also, and most critically, between laboratory results and real-world, in-situ performance.

#### Research Gap and Project Justification

Current research, while valuable, underscores the complexity of this scaling correlation. For instance, a pivotal study (Ref.) demonstrated that identical flow velocities measured in a riverbed and on samples from the same location tested in an Erosion Function Apparatus (EFA) can induce significantly different shear stresses. This discrepancy highlights the necessity of developing site-specific scaling factors to accurately relate phenomena observed at laboratory and field scales. Such limitations indicate that the current state of knowledge remains insufficient, calling for more advanced, integrated investigation.

#### Project Activities and Integrated Response

The European project Bonsai is designed to address this need directly. It includes an extensive programme of in-situ erosion tests on a range of dykes with varying characteristics (soil composition, vegetative cover, construction techniques, and climatic exposure). To scientifically underpin and maximize the value of this field data, the project incorporates a dedicated research work package focused on advancing the correlation between field and laboratory erosion testing.

A central contribution to this objective will be provided by ESTP through two concrete and synergistic actions:

- The design and construction of a novel, versatile laboratory erosion device.
- The funding of a dedicated three-year PhD thesis to model and analyse erosion test correlations.

#### Integrated Methodology and Expected Outcomes

The PhD study will leverage a unique dataset, combining the project's in-situ measurements with systematic laboratory testing using three complementary devices: the Jet Test, the EFA, and the new erosion apparatus. The comparative analysis of results from these different methods, benchmarked against field observations, will enable the development of more robust scaling laws. It will also allow for a precise evaluation of the performance and operational range of the new device.

Therefore, the development of the new erosion meter is not an isolated activity but forms the instrumental core of an integrated research endeavour. It is essential for addressing the identified scientific challenges and for providing infrastructure managers with more reliable tools for erosion prediction and risk assessment.

### Test protocol

To ensure high reproducibility and ensure accurate soil erosion measurements, the testing protocol for the new ESTP erodimeter will be standardized into a well-defined procedure. The following protocol is for overflowing mode only. The protocol will integrate the automation capabilities of the new device to eliminate operator bias, a limitation observed in traditional EFA testing. We can divide the testing protocol into different phases:

#### Phase 1: Sample preparation and installation

We can differentiate between two types of samples to address the BONSAI project's requirements in soil testing: intact and reconstituted samples.

- Intact samples: Soil samples are extracted directly from testing sites using a core-drilling machine equipped with tubes matching the erodimeter's required diameters. To maintain the soil's integrity, the samples will be meticulously trimmed to the specified length.
- Reconstituted samples: For parametric studies (e.g., assessing climate change effects), soils are compacted in specific molds to target densities and moisture levels.
- Saturation: Prior to testing, samples undergo a saturation phase.
- Installation: The sample is loaded into the piston chamber. A "zero-position" calibration is performed where the automated sample positioning system aligns the top surface of the soil perfectly flush with the bottom of the hydraulic channel (protrusion = 0 mm).

#### Phase 2: System initialization

Once the sample is placed in the flume, the hydraulic circuit is initialized to ensure stable testing conditions:

- **Filling and purging:** A low-velocity flow is imposed to fill the entire volume of the testing flume with water, ensuring that all air bubbles are purged from the system.
- **Surface characterization:** Before erosion begins, optical sensors perform an initial scan of the soil surface. This step establishes the reference geometry and measures the initial surface roughness.
- **Test parameter selection:** Based on the soil type identified (e.g. stiff clay, silt ...) and the initial roughness data, the operator can select an appropriate testing program via

the control interface or manually select the testing program (i.e. flow speeds, duration, time interval for roughness measurement ...).

### Phase 3: Automated erosion sequence

The core of the protocol is the execution of the erosion test, which operates on a continuous automated feedback loop:

- **Hydraulic control:** The pump generates the target flow defined in Phase 2. Constant velocities are applied in incremental steps (e.g. increasing by 0.5 m/s), maintained for a fixed duration to test erosion (Different options maybe applied).
- **Real-time detection:** The sensors continuously monitor the position of the soil surface with high frequency. It also captures the state of the surface of a sample during an experiment, granting the user further access to surface roughness of the soil sample during the experiment and the volume of the soil eroded throughout an experiment.
- **Active compensation:** As soon as erosion is detected (surface lowering), the control unit commands the motorized piston to push the sample upwards. The objective is to maintain the soil surface exactly flush with the channel floor ( $\Delta z \approx 0$ ) throughout the test, ensuring no protrusion causing additional drag/hydraulic instabilities.
- **Multi-physics monitoring:** Simultaneously, the system continuously logs data from auxiliary sensors to characterize the flow fully. This includes water temperature (to correct for viscosity changes), flow velocity measured via flowmeters, and shear stress values acting on the interface.

### Phase 4: Data, post-processing and deliverables

Once testing is completed, an automated script will run to postprocess the test results. This postprocessing will include standardizing erosion data outputs, performing statistical analysis, and generating a summary report with key parameters and corresponding graphs.

## Tests UCLouvain and KU Leuven

Laboratory overflowing tests (referred to as medium-scale tests) are being designed to investigate the erosion resistance of different soil compositions, with and without grass cover reinforcement, representing typical levee and dike protection layers. These experiments aim to provide valuable insight into erosion initiation and progression under constant overflow discharge, while offering greater flexibility in test control, data collection, and repeatability compared to full-scale tests.

In addition, medium-scale tests seek to explore correlations between full-scale overflow experiments and small-scale laboratory tests, such as the Erosion Function Apparatus (EFA), by reproducing comparable loading conditions on soil samples taken from the project pilot sites at an intermediate scale.

These reduced-scale erosion tests are carried out within the framework of a joint PhD programme between UCLouvain and KU Leuven, as part of the BONSAI project.

### General description of test equipment

The first experimental setup is located in the hydraulic laboratory in Bruges (KU Leuven campus) and was constructed by two master's students as part of their thesis work. The design consists of a wooden "flume in a flume". The configuration enables producing flow velocities up to 2.5m/s.

This setup is primarily intended to explore the feasibility of medium-scale erosion experiments, to test the performance of different measurement techniques. These include the hydraulic measurements (water levels, velocity, and discharge measuring sensors) as well as morphodynamic monitoring aimed at tracking the spatial and temporal progression of erosion within the soil sample.

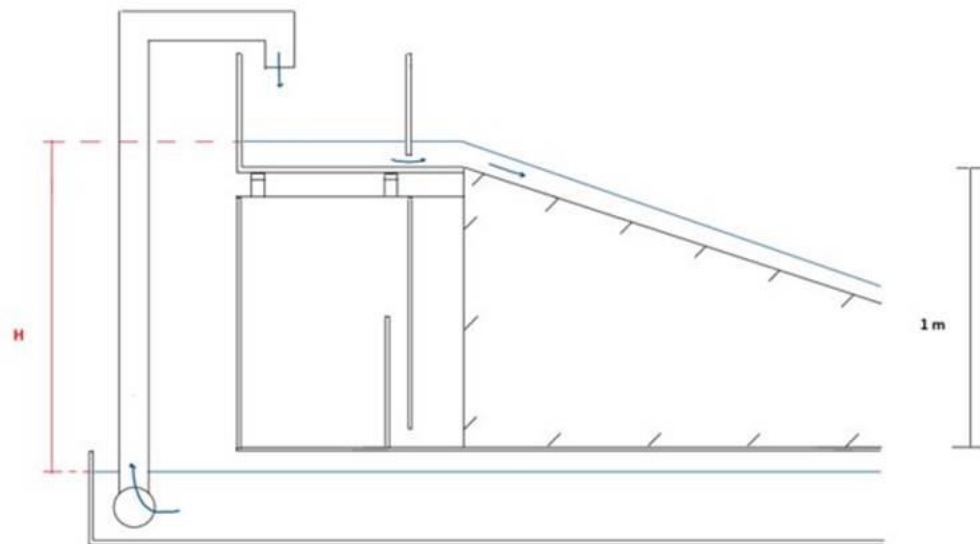


Figure 25 Schematic representation of the Bruges flume setup, designed and constructed by KU Leuven master's students Wout and Seppe.



Figure 26 Experimental setup in Bruges hydraulic laboratory (KU Leuven campus).

Geometry of the setup

The flume has a slope of 1:3, representative of typical levee profiles observed in the field, and a width of 20 cm. The system is supplied by three pumps, each capable of delivering approximately 13 m<sup>3</sup>/h. A modular sample box (20 cm × 100 cm) enables the testing of soil samples under different hydraulic conditions.

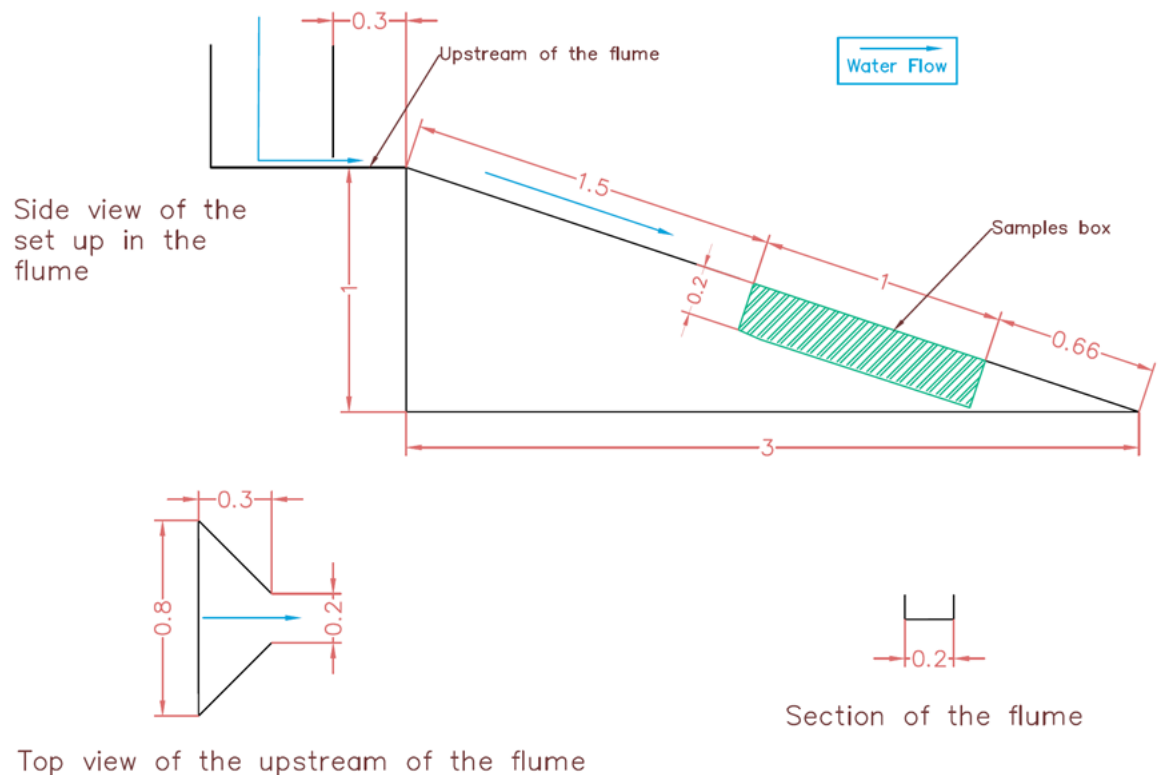


Figure 27 Geometric representation of the experimental setup in KU Leuven Bruges-Campus,.

### Measurement techniques

Several measurement techniques will be tested to evaluate their suitability for overflow erosion experiments within the current setup. The aim is to produce a comprehensive and high-accuracy dataset (water depth, velocity, erosion profiles) that can be used to derive shear stress and to determine erosion rates.

#### *Hydraulic Measurements:*

- **Water level:** comparison between wave gauges, a visual depth gauge mounted on the side wall of the channel, and a simple measuring rod at fixed points.
- **Flow Velocity:** use of a velocity probe and PTV (Particle Tracking Velocimet).

#### *Erosion Monitoring:*

- **Surface evolution:** use of photogrammetry and LiDAR scanning to generate high-resolution digital surface models of the eroded soil.
- **Point-wise measurements:** manual depth readings with a graduated rod to provide reference control points.

### Soil sampling

The sample box (100 cm × 20 cm) is designed to be easily removed and replaced. A key challenge lies in collecting soil samples in one piece, in order to avoid weak points that could bias erosion behaviour. Ensuring proper sample collection and preparation is therefore an integral part of the experimental work.

### Aim and site suitability

The Bruges setup serves as a first exploratory step to understand the possibilities of conducting erosion experiments in a flume. It provides a cost-effective alternative to large-scale field trials while offering more realistic hydraulic conditions than small laboratory devices (like EFA or JET).

The research questions guiding this work include:

- Is it possible to reproduce the erosion of vegetation cover in a medium-scale test device?
- To what extent can a medium-scale test device be representative of real levee behaviour?
- Can the results obtained be linked to theoretical erosion models and numerical simulations?

Although the current setup represents an initial stage, several improvements are foreseen. One option under consideration is the transfer of experiments to a larger flume equipped with more powerful pumps, thereby enabling higher flow velocities and broader testing conditions. Following the work initiated by the master's students, the setup will continue to be analysed and refined wherever possible. The results will also be used to be compared to model.

### Contribution to overall objective

The medium-scale setup provides aims to provide a methodological bridge between small laboratory tests (EFA, JET) and large-scale pilot activities. By quantifying erosion of soil samples under controlled conditions, the tests generate data that can be used to calibrate models and validate erosion resistance thresholds.

**Link with other pilot actions**

If the current setup proves conclusive, soil samples collected from pilot sites can be tested in the flume to compare their behaviour across scales. The setup can also be modelled numerically and compared with field observations, thereby strengthening the coherence between modelling, small, medium-scale, and large-scale erosion studies.

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## PART 2: Animal burrows

## Introduction Activity 2.3: Animal burrows

This test plan describes how BONSAI Action A2.3 – Joint Pilot Action for Short-Term Robustness: Animal Activities will generate practical, evidence-based knowledge to support levee managers in assessing and mitigating risks caused by animal burrowing.

### The plan defines:

- the problem and urgency,
- the positioning of BONSAI relative to parallel initiatives,
- the key knowledge gaps,
- the specific research questions and deliverables, and
- the methods, locations, planning, and organisation of the work.

The overarching aim is to support a shift from reactive inspection-based management to proactive, risk-based decision-making regarding animal activity in earthen levees across North-West Europe (NWE).

### Problem description

Earthen levees are a critical component of flood protection in the estuarine systems across NWE, safeguarding large populations and major economic assets. As predominantly green structures, levees attract burrowing animals such as **moles, foxes, rabbits, badgers, and increasingly beavers.**

Animal burrowing can:

- alter seepage and hydraulic behaviour,
- trigger internal erosion, instability, or surface erosion,
- significantly reduce levee reliability during extreme events.

Recent full-scale overflow and wave-overtopping experiments in the Netherlands and Belgium showed that the presence of animal burrows can lead to **rapid and sometimes catastrophic erosion**. These experiments also demonstrated that burrow systems, particularly those created by small animals, are often **far more extensive than assumed**.

Despite these risks:

- animal activity is not explicitly addressed in levee design standards,
- management relies heavily on inspection and maintenance,
- levee managers lack validated tools to assess when damage becomes critical.

The challenge is intensified by:

- growing populations of protected species (e.g. beavers, badgers),
- legal and ecological constraints on intervention,
- climate change increasing the frequency and severity of hydraulic loading.

This combination creates an urgent need for **systematic knowledge, validated methods, and integrated decision frameworks**.

### Positioning BONSAI within ongoing initiatives

BONSAI seeks to enhance collaboration, fill knowledge gaps, and contribute to a coherent NWE-wide approach to managing animal-induced risks in levees by focusing on **cross-border learning, joint field campaigns, and systematic comparison of methods,**

Over the past five years, the urgency of animal-induced levee damage has led to several national and regional initiatives, particularly in the Netherlands and Belgium, but also in Germany and other NWE countries. Key examples include:

- *Dieren in de Dijk* (Regieorgaan SIA – HZ): a collaboration applied research project in the Netherlands and Belgium focusing on formalizing and sharing knowledge on animal burrows characteristics on levees, their management, including detection, inspection and deterrence measures and their influence of levee safety.
- *Veiligheidsraamwerk Dierlijke Graverij* (HWBP – Deltares): research project focusing on the advancement of an approach to integrate the risk of animal burrows in the official levee assessment approach of the Netherlands.
- *Kenniscentrum Bever (Dutch consortium)*: consolidating best practices on beaver management, including levee safety, including application and monitoring of high water refuges for beavers and beaver tracking.
- *Bevers en (Water)veiligheid*: a collaboration applied research project in the Netherlands that focuses on collecting data from beaver tracking and integrating the collected data into the decision making practices of regional water authorities in the Netherlands.

These initiatives have significantly advanced awareness and local practice. However, outcomes remain context-specific, and rarely validated across regions or climates. The BONSAI project aims to **complement and strengthen** the outcomes of these initiatives rather than duplicate efforts.

# BONSAI Activity A2.3 – Joint pilot action on animal Activity

## Scope and deliverables

Action **A2.3** aims to strengthen the scientific and practical basis for managing animal-induced risks to levees across NWE. **Partners involved** include HZ, STOWA, Rijkswaterstaat (RWS), University of Lille (ULille), Cerema, De Vlaamse Waterweg (DVW), Dienst Mobiliteit en Openbare Werken (DMOW), and INBO.

The action contributes to the following deliverables:

- **D2.3.1** Report on inspection, detection and monitoring methods for animal activities
- **D2.3.2** Report on digging capacity and risks per animal and climate zone
- **D2.3.3** Evaluation report on animal behaviour
- **D2.3.4** Classification system for sensitivity of levees to animal effects
- **D2.3.5** Risk profiling approach for evaluating levee sensitivity to animal effects.

## State of the art and key knowledge gaps relevant to A2.3 deliverables

Animal burrowing is a recognised threat to levee integrity in North-West Europe. While awareness of the problem is high, knowledge relevant for **operational inspection, risk assessment, and decision-making** remains fragmented. This section presents the state of the art strictly in relation to the themes addressed by Deliverables D2.3.1–D2.3.5 and highlights the associated knowledge gaps that motivate the planned activities.

## Current knowledge and practice

Levee managers currently rely primarily on **visual inspections** to detect animal burrows. These inspections are cost-effective and widely implemented but strongly depend on inspector experience and provide limited information on subsurface geometry.

To overcome these limitations, a wide range of **non-intrusive detection techniques** has been explored in research and pilot projects, including:

- Ground-penetrating radar (GPR, including 3D-GPR)
- Electrical resistivity tomography (ERT)
- Sonar and remotely operated vehicles (ROVs)
- Thermal imaging
- Wildlife cameras and tracking dogs
- LiDAR scanning and photogrammetry

More recently, **emerging techniques** such as environmental DNA (eDNA), fibre-optic sensing, and animal transmitters have been proposed as potentially valuable tools.

It is broadly recognised that **no single technique** can provide complete information on burrow presence, geometry, and development, particularly for complex systems such as beaver burrows. Combined use of multiple techniques is therefore often recommended.

## Key gaps

- No systematic comparison of detection and monitoring techniques across levee types, animal species, and site conditions
- Limited validation of detection accuracy at known burrow systems
- Lack of guidance on which combinations of techniques are most effective in specific contexts

- Insufficient information on feasibility, robustness, user experience, and costs

These gaps directly motivate Deliverable D2.3.1.

#### Burrow geometry, digging capacity and damage characteristics (D2.3.2)

##### **Current knowledge and practice**

Qualitative knowledge exists on the types of animals active on levees in North-West Europe and on their typical burrowing behaviour. Literature and practitioner experience describe general burrow characteristics for species such as muskrats, coypu, badgers, and beavers.

However, most available information is **descriptive** and often derived from incidental observations during inspections or repairs. Data on burrow dimensions are typically incomplete and rarely linked to environmental conditions such as soil type or vegetation.

##### **Key gaps**

- Limited quantitative data on burrow geometry, volume, depth, and spatial density
- Poor understanding of how burrows grow and evolve over time
- Lack of comparative data across climate zones, soil types, and levee designs
- Absence of consolidated overviews linking animal species to typical damage patterns

These gaps are addressed in Deliverable **D2.3.2**.

#### Drivers of animal behaviour on levees (D2.3.3)

##### **Current knowledge and practice**

It is generally accepted that animal activity on levees is influenced by a combination of factors, including:

- Soil type and moisture conditions
- Vegetation cover and root structure
- Water levels and hydraulic dynamics
- Energy efficiency of burrowing

These relationships are primarily understood **qualitatively**, based on ecological studies and expert judgement.

##### **Key gaps**

- No quantitative prioritisation of behavioural drivers relevant for levee safety
- Limited site-specific data linking environmental parameters to observed burrowing activity
- Insufficient integration of ecological insights into levee management and risk assessment

These gaps underpin Deliverable **D2.3.3**.

#### Sensitivity and vulnerability of levees to animal activity (D2.3.4)

##### **Current knowledge and practice**

Some levee managers apply **local or national risk profiling approaches** to assess vulnerability to animal burrowing, often as part of broader asset management or inspection frameworks. These approaches typically combine expert judgement with available inspection data.

However, methodologies vary widely between regions and countries, and the criteria used are not harmonised.

**Key gaps**

- No unified framework to classify levee sensitivity to animal-induced damage across NWE
- Limited transferability of local approaches
- Weak linkage between detection results, burrow characteristics, and vulnerability classification

Deliverable **D2.3.4** aims to address these gaps by developing a common classification approach

Risk assessment and failure probability related to animal burrows (D2.3.5)

**Current knowledge and practice**

Animal burrows are known to contribute to several levee failure mechanisms, including internal erosion, micro-instability, and external erosion. Experimental studies and expert assessments indicate that burrows can significantly increase failure probability.

Some analytical and numerical models exist to describe failure processes, and expert-based probability estimates are occasionally used in practice. However, these approaches remain difficult to apply consistently.

**Key gaps**

- Lack of a unified risk assessment framework explicitly addressing animal burrows
- Insufficient models linking burrow geometry and location to failure probability
- High uncertainty in probability estimates due to missing empirical input data
- Strong reliance on expert judgement without systematic validation

These gaps form the core motivation for Deliverable **D2.3.5**.

**Synthesis**

Across all deliverables, the state of the art is characterised by **qualitative understanding, fragmented data, and limited validation**. The BONSAI A2.3 activities are therefore designed to:

- Generate empirical data where it is currently missing
- Systematically test and compare methods and approaches
- Integrate ecological, geotechnical, and asset-management perspectives
- Translate findings into practical tools for levee management authorities

This focused approach ensures that the state-of-the-art gaps identified above are directly addressed by the planned deliverables.

# Global rationale and activity structure

In response to the knowledge gaps identified in the state-of-the-art review (Section 4), Action A2.3 combines empirical data collection, expert knowledge, and synthesis activities. The approach is deliberately structured to generate **quantitative input data, validated methods, and decision-support elements** required for Deliverables D2.3.1–D2.3.5.

Activities supporting A2.3 are organised into three complementary categories:

1. **Field campaigns** – generation of empirical data
2. **Expert judgement** – structured elicitation to address data gaps and uncertainties
3. **Desk research** – analysis, synthesis, and integration of results

Together, these activities ensure consistency between observed animal activity, detection techniques, behavioural understanding, and risk assessment outcomes.

## Field campaigns

Field campaigns form the empirical backbone of Action A2.3. They directly address gaps related to **burrow geometry, spatial extent of animal activity, and the performance of detection and monitoring techniques** identified in the state-of-the-art review.

The primary objectives of the field campaigns are to:

- Quantify animal-burrow geometry, density, and spatial distribution
- Test and compare inspection, detection, and monitoring techniques under real-world conditions

Campaigns are conducted mainly outside the official BONSAI pilot sites, where animal activity is often limited, while still including selected BONSAI sites for reference and comparability.

## Expert judgement elicitation sessions

Structured expert-judgement sessions complement the field campaigns by addressing parameters that cannot be directly measured or remain highly uncertain. These sessions explicitly support the development of deliverables related to **behavioural drivers, failure mechanisms, and risk assessment**.

Two thematic streams are addressed:

- Physical processes relevant to levee safety (e.g. failure paths associated with burrows)
- Ecological and behavioural parameters influencing animal activity

Methods include tabletop exercises and structured elicitation formats to ensure transparency and reproducibility.

## Desk research

Desk research integrates and synthesises information from field campaigns and expert judgement with relevant scientific and technical literature. It focuses on:

- Processing and analysing collected datasets
- Identifying patterns and correlations across sites and techniques
- Translating results into structured overviews, classifications, and frameworks
- Development of a risk profiling approach for geotechnical failure

Desk research supports all deliverables and ensures coherence between empirical findings and methodological development.

# Rationale, objectives and key actions per deliverable

The following sections describe how the identified knowledge gaps are addressed through specific objectives and activities for each deliverable.

## Inspection, detection and monitoring methods for animal activity (D2.3.1)

### Rationale

As identified in Section 4.1, no single inspection or detection method is sufficient, and systematic comparisons of techniques and combinations are lacking.

### Objective

To provide a structured comparison of the feasibility, effectiveness, and costs of inspection, detection, and monitoring techniques, and their combinations, across different levee types, animal species, and site conditions.

### Key actions

- Apply identical detection methods at multiple locations to assess robustness and feasibility
- Apply multiple methods at known burrow systems to compare detection accuracy
- Focus on (3D-)GPR and ERT applications (Cerema / ULille), complemented by other available techniques
- Analyse performance, limitations, and cost aspects (desk research)
- Validate and formalise findings through consortium workshops

## Digging capacity and damage characteristics per animal and climate zone (D2.3.2)

### Rationale

Section 4.2 highlighted the lack of quantitative data on burrow geometry, spatial density, and development over time, as well as their dependence on environmental conditions.

### Objective

To provide consolidated overviews of typical animal-induced damages on levees, differentiated by animal species, levee type, and climate zone.

### Key actions

- Measure burrow dimensions, volumes, and spatial density at multiple locations
- Collect soil and vegetation data at the same sites
- Analyse relationships between burrow characteristics, soil properties, and vegetation
- Compile species-specific overviews of damage configurations
- Compare field results with literature findings (desk research)
- Validate results through expert workshops

## Evaluation of animal behaviour relevant to levee safety (D2.3.3)

### Rationale

As identified in Section 4.3, behavioural drivers are known qualitatively but lack prioritisation and quantitative support for levee applications.

### Objective

To clarify and prioritise the environmental and structural factors influencing animal activity on levees across climate zones.

### Key actions

- Analyse environmental parameters at surveyed locations (desk research)

- Conduct targeted vegetation surveys in collaboration with the Biodiversity group
- Integrate behavioural insights with observed burrowing patterns
- Verify and formalise findings through expert workshops

#### **Classification system for sensitivity of levees to animal effects (D2.3.4)**

##### **Rationale**

Section 4.4 identified the absence of a harmonised approach to classify levee vulnerability to animal-induced damage across North-West Europe.

##### **Objective**

To develop a North-West Europe-wide classification system for levee sensitivity to animal effects that supports operational, tactical, and strategic decision-making.

##### **Key actions**

- Compare vulnerability and risk profiling results across different regions
- Identify transferable classification elements
- Align the classification system with asset management practices of levee authorities
- Consolidate the approach through workshops and desk research

#### **Risk profiling and assessment framework for animal effects on levees (D2.3.5)**

##### **Rationale**

As discussed in Section 4.5, risk assessment frameworks explicitly addressing animal burrows are fragmented, data-poor, and strongly dependent on expert judgement.

##### **Objective**

To develop a practical risk assessment framework enabling levee management authorities in North-West Europe to assess breach risk related to animal activity at the levee-segment scale.

##### **Key actions**

- Review existing risk assessment frameworks (e.g. Deltares/RWS)
- Use structured expert judgement to address missing parameters
- Model failure processes related to animal burrows (ULille)
- Conduct site-specific risk assessments in selected locations (e.g. Dijke, Doeldijk, Zeeland)
- Test erosion processes and emergency repair measures for animal burrows
- Develop a risk profiling tool for levees and integrate new insights into the tool, allowing sensitivity analyses and scenario-based assessment of geotechnical failure mechanisms

# Overview of field campaigns and test locations

This section provides an overview of the field campaign locations supporting Action A2.3. The selection of sites directly reflects the objectives of Deliverables D2.3.1–D2.3.5 and is designed to capture variation in animal species, levee types, soil and vegetation conditions, and hydraulic and climatic contexts.

As agreed during the early stages of BONSAI, the field campaigns for animal burrows deviate from the official BONSAI pilot sites. Animal activity hotspots are highly specific and often absent from the generic pilot locations. Selected BONSAI sites are nevertheless included where relevant for comparison and integration. Several actions described below have already been executed or are currently under development in collaboration with related initiatives, in particular *Dieren in de Dijk*, *Bever & Waterveiligheid*, and *Kenniscentrum Bever*. These collaborations ensure continuity with existing knowledge development and avoid duplication of effort.

## Field campaigns supporting D2.3.1, D2.3.2 and D2.3.3

*(Inspection and detection methods, burrow geometry, and animal behaviour)*

### Fort Everdingen (NL) – Beaver

At Fort Everdingen, a levee section protected with steel sheet piling allows controlled observation of beaver burrows without the need for immediate repair. Active burrow systems are present. The site was inspected in March 2025 using avalanche sensors, RobotMol, and GPR, and the results are currently being processed. The site offers a strong opportunity to repeat GPR and complementary measurements in the first half of 2026 to capture the temporal development of burrow-related anomalies. This location primarily supports the evaluation of detection techniques and the monitoring of burrow evolution.

**Participating partners:** HZ, ULille, Cerema

### Zwolle and Oijen (NL) – Beaver

In Zwolle and Oijen, high-water refuges have been installed with the aim of diverting beavers away from levees. These structures are currently being monitored to assess their usage by beavers. Preparations are underway to track individual animals, and a dedicated monitoring plan for the refuges is being developed. This work is initiated through the Kenniscentrum Bever and the *Bever & Waterveiligheid* project and provides a continuous observation opportunity under varying weather and water-level conditions up to June 2027. The site primarily supports Deliverable D2.3.3 on animal behaviour.

**Participating partners:** HZ, STOWA

### Dijle (BE) – Beaver

Along the Dijle, beaver activity is present in levee sections where water levels can be actively regulated by DWV. This makes the site particularly suitable for inspection and detection exercises under controlled hydraulic conditions. A drone survey was conducted in October 2025, and there are opportunities to repeat and expand measurements in the second half of 2026. The site contributes mainly to Deliverables D2.3.1 and D2.3.2.

**Participating partners:** HZ, De Vlaamse Waterweg (DWV), MOW

#### Doeldijk (BE) – Fox and rabbit

At Doeldijk, levees are affected by fox and rabbit activity. The area is easily accessible and well suited for repeated inspections using different detection techniques. In addition, the site allows combined soil and vegetation surveys, enabling extension of burrow geometry and damage characterisation to non-aquatic species. Field activities are planned for the period May-July 2026, with opportunities for repeated or refined surveys during the same period in 2027. This location supports Deliverables D2.3.1, D2.3.2 and D2.3.3.

**Participating partners:** HZ, DVW, INBO, ULille, Cerema, MOW

#### Vught (NL) – Beaver

At Vught, drone surveys were planned in collaboration with the Ministry of Defence for January 2026 but were postponed due to unforeseen drone damage. The site remains a potential location for testing remote sensing and subsurface detection techniques for beaver activity. In addition, it offers opportunities for a joint survey of beaver activity and vegetation in collaboration with the Biodiversity group. This latter activity is not yet confirmed but could take place in the first half of 2027. The site supports Deliverable D2.3.1 and contributes behavioural insights relevant to D2.3.3.

**Participating partners:** HZ, Ministry of Defence, INBO

#### Zeeland (NL) – Mole

In Zeeland, six levee locations prone to both wave overtopping and mole activity were monitored systematically in the first half of 2026. Soil samples from these locations have been analysed in the HZ laboratory. Follow-up mapping of mole activity is planned for September-December 2026, involving HZ students. A GPR survey was conducted in September 2025 and is planned to be repeated within 2026. The site also offers opportunities for ERT surveys and for vegetation surveys in coordination with the Biodiversity group, although the latter is not yet confirmed. These actions support Deliverables D2.3.1, D2.3.2 and D2.3.3.

**Participating partners:** HZ, INBO, ULille, Cerema

#### Additional and prospective locations

To strengthen coverage across climate zones, additional test sites in France and Germany will be explored. Joint vegetation-animal surveys are currently being discussed for Zeeland and Vught in coordination with the Biodiversity group, with final site selection still to be confirmed.

### Field campaigns supporting D2.3.5

*(Risk profiling and failure processes)*

#### Marnewaard, Paddepoel and Flood Proof Holland (NL)

Several locations are considered for actions supporting the development and validation of the risk profiling and assessment framework. These include Marnewaard (NL), Paddepoel (NL), and Flood Proof Holland (NL), with Flood Proof Holland already confirmed. Actions at Flood Proof Holland are scheduled to start in April 2026 and run for approximately 18 months.

At these sites, artificial animal burrows may be constructed to investigate the effect of burrow geometry on levee strength, to test erosion and failure processes under controlled conditions, and to evaluate emergency repair and closure techniques. Collaboration with crisis management and disaster response partners is envisaged, and coordination with the crisis management team is ongoing for sites other than Flood Proof Holland.

**Participating partners:** HZ, Cerema, RWS, ULille, STOWA, MinDef.

# Overview of desktop studies

## Risk profiling approach for levees (D2.3.5)

### Context and rationale

This deliverable focuses on the development of a risk profiling approach to support the evaluation of the sensitivity of levees to geotechnical failure mechanisms. The activity aims to strengthen how levee managers assess and prioritise risks at the scale of individual levee segments or regions, taking into account both hydraulic loading and structural vulnerabilities.

It provides the framework to further develop an integrated, GIS-based risk profiling tool, supporting a more consistent and transparent assessment of levee sensitivity under current and future conditions. The approach explicitly recognises that geotechnical failure risk is influenced by a combination of factors, including hydraulic conditions, levee characteristics and external stressors, like animal burrows.

### Description

We will further develop a risk profiling tool that evaluates the susceptibility of levee segments to different geotechnical failure mechanisms. The tool combines a wide range of input parameters related to hydraulic loading, levee geometry, material properties and aggravating factors, and translates these into relative risk scores for multiple failure modes.

Within BONSAI, the emphasis lies on:

- migrating existing assessment methods towards an online, database-driven environment;
- increasing the level of automation in data handling and calculations;
- improving the consistency and updateability of risk assessments over time;
- enabling scenario-based analyses, allowing sensitivity checks under varying conditions and assumptions.

Rather than focusing on a single stressor, the risk profiling tool is designed to remain generic and extensible, so that new parameters or insights can be integrated as knowledge evolves.

### Expected outcomes

The expected outcomes of Deliverable D.2.3.5 include:

- a strengthened risk profiling approach supporting levee management and prioritisation,
- improved insight into the relative sensitivity of levee segments to geotechnical failure,
- clearer support for decision-making regarding inspection, monitoring and mitigation efforts,
- and a framework that can evolve as new knowledge becomes available within the BONSAI-project.

The deliverable does not aim to provide a fully validated predictive tool, but rather a robust and practical framework to support risk-informed decision-making.

## Planning of actions

### Global planning of activity A2.3 (Q1 2025 – Q3 2028)

	2025	2025	2026	2026	2027	2027	2028	2028
	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4
Field campaigns		■	■	■	■			
Expert judgement sessions		■	■	■	■			
Desk research / data processing		■	■	■	■	■	■	
Reporting						■	■	■

### Indicative planning of field campaigns (Q1 2025 – Q3 2028)

The table below provides an indicative overview of field campaign actions. Timing may be refined as coordination with partners and external projects progresses

Site / Activity	2025				2026				2027				2028		
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Fort Everdingen – inspections & GPR	■				■	■									
Zwolle & Oijen – refuge monitoring & beaver tracking		■	■	■	■	■	■								
Dijle – detection & drone surveys			■				■	■							
Doeldijk – inspections & soil/veg						■	■			■	■				
Vught – drone & joint surveys					■				■						
Zeeland – mole mapping & GPR			■		■	■	■								
FR/DE additional sites					■	■			■	■					
Flood Proof Holland – artificial burrows					■	■	■	■	■						
Paddenpol - artificial burrows									■	■	■				
Maarnewaard - artificial burrows									■	■	■				

■ confirmed    ■ not confirmed yet

### Indicative planning of expert judgement elicitation sessions (Q1 2025 – Q3 2028)

Expert judgement elicitation session	2025				2026				2027				2028		
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Expert judgement: Erosion rates - moles				■											
Expert judgement: Failure paths & flood safety - beaver							■	■				■	■		
Expert judgement: Ecological behaviour animals							■	■							
Focus group: Emergency closure animal burrow					■	■									

■ confirmed    ■ not confirmed yet

## Organisation and coordination

From January 2026 onwards, partners involved in Action A2.3 will meet every six weeks to coordinate actions, monitor progress, and address emerging needs. The consortium is committed to educating the next generation by involving students through internships, MSc theses, and PhD research wherever possible, and by integrating animal-burrow-related topics into WP3 actions such as the Flood Academy, summer schools, and curriculum development