# Embedded structures in flood defenses
## Effects on safety and failures

Aguilar Lopez, Juan

**Publication date**
2017

**Document Version**
Final published version

**Published in**
Integral Design of Multifunctional Flood Defenses

Figure 1. Piping and wave overtopping erosion based failure mechanisms may contribute o 48 percent of the total failure probability of a dike.

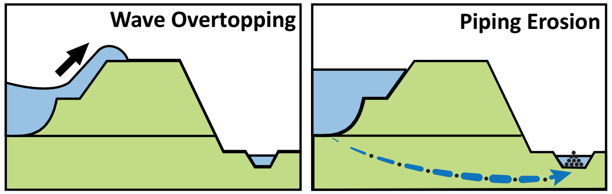
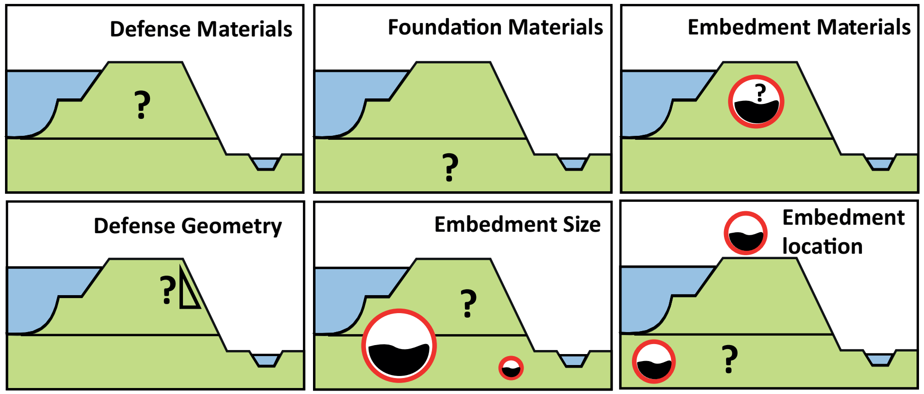



Figure 2. MFFD design choices: Material choices (top row below) and dimension choices (bottom row below).






Juan Pablo Aguilar-López

# EMBEDDED STRUCTURES IN FLOOD DEFENSES

## EFFECTS ON SAFETY AND FAILURES

*Dr.ir. Juan Pablo Aguilar-López works as a Postdoc at Delft University of Technology, faculty of Civil Engineering & Geosciences, department of Water Resources. In the MFFD program he was a PhD candidate at Twente University of Technology, faculty of Engineering Technology (CTW) in the project 'Safety and reliability assessment of multifunctional flood defenses'. Juan Pablo graduated in 2016.*

*Dissertation title:*
*'Probabilistic safety assessment of multi-functional flood defences.'*

*PhD Supervisors:*
*Prof.dr. Suzanne Hulscher, University of Twente*
*Dr. Jord Warmink, University of Twente*
*Dr. Ralph Schielen, University of Twente*

Flood defenses are exposed to deterioration processes that compromise their stability. These processes are called 'failure mechanisms' and they are mostly triggered and/or exacerbated by the hydraulic loads generated during extreme high water events, which are becoming more frequent due to climate change. Concepts such as the 'Delta dike' or the 'Unbreachable dike' have been developed in the Netherlands to deal with these failure mechanisms.

These approaches resulted in the design of massive flood defenses that can withstand extreme water events thanks to their larger dimensions and highly resistant materials. However, these characteristics should be optimized to make them cost effective.
A good way to achieve this goal is to use the initial space allocated exclusively for flood defense in combination with additional functions. These extra functions may also help to reduce their required size to cope with the failure mechanisms, but in order to do this, we need to quantify the additional resistance provided by the embedded structures.

Multifunctional flood defenses (MFFDs) are often represented as large and robust structures where large infrastructure may be allocated. However, multifunctionality is defined only by the type and number of functions and not by the size of the structure itself. In that sense, common flood defense structural embedments such as dikes with roads, pipeline crossings through and under the flood defenses, and buildings embedded within the dikes can also be considered as multifunctional flood defenses. Moreover, large scale MFFDs usually include habitable spaces, which means that access and sanitation infrastructure will almost always be embedded in them as well.

*Failure mechanisms and design choices*
In the current Dutch context, national legislation for flood management is moving towards a risk-based policy, where systems are evaluated based on the probability of flooding and the resultant consequences of an specific event. The probability of flooding is determined by the reliability of the flood defenses for different evironmetnal loads. MFFDs will definitely be exposed to the same failure mechanisms as conventional flood defenses due to these loads. However, the frequency of failure will change not only due to the effects of climate change and sea level rise, but also because of the additional structures now included in the flood defenses.

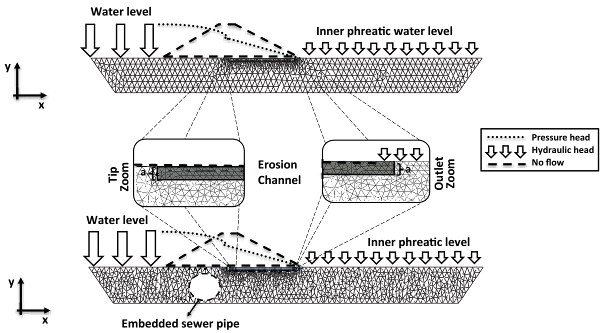
Extensive research performed around the world and particularly in the Netherlands, has shown that from all the possible failure mechanisms, two of them may account for as much as 48% of the total estimated failure probability. These failure mechanism are the Backward piping erosion and the wave overtopping (Figure 1).

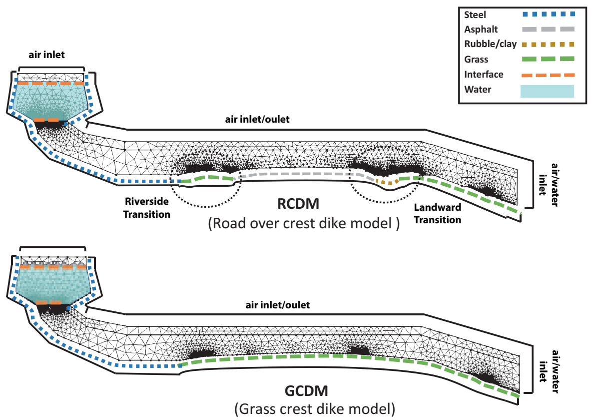
- *Backward erosion (piping):* Collapse of the granular foundation due to cavity formation (also known as pipes) derived from fine sediment transport towards the landward side.
- *Wave overtopping:* Landward slope erosion of the grass cover on the landward side caused by overtopped waves.

From a structural design point of view, it is interesting to quantify how the change of dimensions and the inclusion of hard structures influence the failure probability of these two main failure mechanisms depending on possible design choices (Figure 2). The design choices may be categorized into material choices and dimension choices and the combination of them are the ones that determine the flood defense reliability.

*Figure 3 (below). Piping erosion FEM model boundary conditions of the IJKDIJK experiment.*

*Figure 4 (below below). Wave overtopping FEM model boundary conditions of Millingen WOS experiment.*




Though all the failure mechanisms will eventually result in a dike breach, each is directly linked to a certain part of the dike. For the case of piping erosion, the foundation is eroded; whereas for wave overtopping the outer grass cover is eroded (Figure 1). Hence the location and size of the embedded structure(s) is the design choice (Figure 2) which may directly influence a particular failure mechanism. The defense geometry will also have an influence but the ideal way to quantify the effects of the embedment is by benchmarking. This means that and initial monofunctional flood defense is compared with one identical in terms of materials and geometry but including the additional embedments.

In order to perform such benchmarking, detailed finite element models (FEMs) were used to simulate both MFFDs with high level of detail. These models allow to simulate the physical processes, while including extreme flood events and the main characteristics of the structures in the analysis as external triggering conditions. FEMs allow us to find the approximate solution of boundary value problems for the partial differential equations which describe the governing physics of each failure mechanism. In our case, each of the two failure mechanism can be described by a different physical process: Groundwater Darcy flow for backward piping erosion; and Navier-Stokes fluid flows flow for wave overtopping.

*Structural embedment cases*
When possible, the result of any model should be compared with the reality which in our case is represented by the measured values of two large scale experiments performed in the Netherlands; the IJkdijk piping erosion experiment and the Wave overtopping simulator experiment (page 40-41). Extensive amount of data was collected during these two real scale filed experiments which allowed to validate both later FEM models.

The first experiment consisted simulating a controlled failure of an artificial dike built with realistic dimensions, which was tested with a lateral water load. The artificial dike was monitored in terms of preassures, displacements and inner temperature in order to understand better the physical processes that governed the piping erosion failure mechanism. The second experiment consisted in placing the wave overtopping simulator (WOS) on the crest of a dike which had a road on top. Later, random water volumes which followed a predefined statistical distribution where released during representative storm durations in orde to test the dike erosion resistnce during wave overtopping extreme events. Volumes, valocities and scouring depths where measured in order to understand the process and validate the actual modeling approaches. Based on the measured data of the two experiments, two FEM models (Figures 3 and 4) where calibrated and validated for different loading conditions tested in the field.

Once the models are accepted as sufficiently representative of reality, the failure probabilistic analysis is conducted by representing the hydraulic loads and the characteristics of the structures as statistical distribution which allow to represent their associated uncertainty. Such distributions are represented in the models as random variables. This means that each variable used in the model follows a probabilistic distribution which can be later sampled during different model runs. One sampling at the time of all involved variables are then used as the model input for one single run of the model. After running a large number of combinations of samples, a probabilistic distribution of the output is obtained. Based on a predefined safety criterion for each failure mechanism (e.g., values of pressure, deformation or scouring depth), these distributions are used to estimate the probability that these values will be exceeded.

*Materials effects: random variable correlation*
The different climate and material scenarios are represented by the chosen input variables and their statistical distributions and therefore their correct selection and representation will also determine the MFFD estimated reliability. Such selection also include their joint occurrence, In other words, it is not only important to select the statistical distribution that will better represent each material characteristic but also the correlation between variables. Correlation determines the degree of joint occurrence between two or more variables. For example, during a extreme storm, high wind speeds will definitely influence the occurrence high wave heights. If both characteristics are used and represented as statistical distributions in one single model, their joint occurrence should also be included during the random sampling of both variables. This joint occurrence may be represented by joint correlation models known as 'copulas'. These copulas not only allow to represent two or more probabilistically correlated variables but also allow to give more importance for large or small values during the sampling process. This is important for MFFDs as the correct representation of correlation will have a significant effect in the estimated reliability of the flood defense for each particular failure mechanism.

*Surrogate modeling for faster computing*
The FEM models are very powerful, but their computational burden is also high. This means that it may not always be possible to conduct sufficient model runs to calculate the failure probabilities. In those cases, surrogate modeling becomes a powerful tool for probabilistic assessment based on FEM models. Surrogate models or 'emulators' are computationally inexpensive models that are trained and validated based on the original input and output values obtained from more complex models such as the FEMs. In other words, fewer FEM model runs are used to built a surrogate which runs faster and therefore it can be used for larger amount of calculations. Different algorithms such as artificial neural networks, decision trees, support vector machines and response surfaces are commonly used for building the surrogates as they are capable of representing highly nonlinear process while reducing the computational time by an order of magnitude. These models allow the original probabilistic distributions of the input to be changed and represent different uncertainty scenarios. Surrogate models were used to test the effect of different water events and different material uncertainties on the two different structural embedment cases.

*Main results*
Overall, the results indicate that having embedded structures under, inside, and on top of flood defenses has significant effects on the safety of these flood defenses. It is expected that these effects become more in the case of more extreme flood events. Large MFFDs are intended to withstand such events, but other smaller MFFDs as the ones found in the actual Dutch landscape, may only withstand such events if the embedded structures are correctly positioned and dimensioned. These smaller MFFDs are often found in the flood defense systams as a consequence of the urban development requiremets and not conceived as integral solutions. While their safety is always assessed by experts in order to ensure that they don't compromise the overall system reliability, is not common to include the embedment effects in the actual probabilistic models. Note that, these effects are not only harmful by catalyzing failure mechanisms, but also beneficial by increase the flood defense resistance or dissipating the energy of the hydraulic loads.

Our approach showed that surrogate modeling was able to capture the additional embedment effects in the probabilistic results, as long as they where incuded in the original complex model. In addition, the correct inclusion of correlation between variables which are used as inputs for the original and surrogate models also have an important influence in the estimated failure probabilities and consequently in the required MFFD dimensions which also determine the size and location of future embedments. Surrogate modeling techniques in combination with correlation modeling are expected to have an enormous potential for the MFFD probabilistic design. We recommend further studying the possibility to develop a generalization of the method so that in the future one robust surrogate model can be used for different locations.