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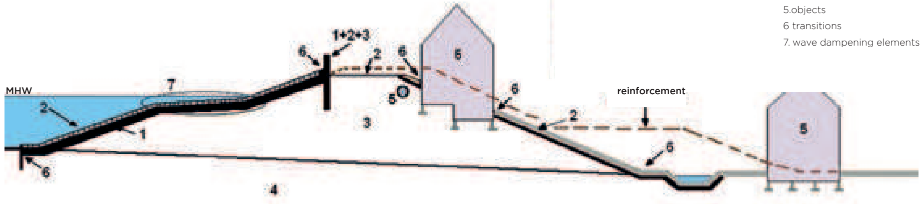
Figure 1 (below). Hypothetical flood defense with all element types present.

Figure 2 (below below). Structure built into dike. at Schoonhoven.

Legend
1 water retaining element
2. erosion-proof element
3 supporting element
4 subsoil
5.objects
6 transitions
7. wave dampening elements



Mark Voorendt

STRUCTURAL EVALUATION OF MULTIFUNCTIONAL FLOOD DEFENSES

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Flood risk reduction aims to minimize losses in low-lying areas. One of the ways to reduce flood risks is to protect land by means of flood defenses. The Netherlands has a long tradition of flood protection and, therefore, a wide variety of technical reports written and guidelines developed for designing and assessing typical flood defenses. These documents have been prepared by the Dutch Technical Advisory Committee for the Flood Defenses (Technische Adviescommissie voor de Waterkeringen, TAW) and apply to dunes, lower and upper river dikes, lake and sea dikes, water-retaining hydraulic structures, etc. These documents contain methods and criteria to determine the reliability of flood defenses, based on the present state of technology and research.

Due to continuously expanding urban activities and the need to improve the present protection level, flood defenses are often combined with structures that serve other functions than flood protection. Examples of these multifunctional flood defenses are parking garages in quays, houses whose façades retain water and wind turbines on dikes. However, the current TAW guidelines are not suitable to multifunctional structures, since they assume specific shapes of flood defenses, like gates or embankments. Multifunctional flood defenses, conversely, consist of atypical structural elements that require a different approach. The lack of official standards or guidelines causes difficulties in estimating whether these multifunctional flood defenses are sufficiently reliable or not. Consulting engineers and research institutes like Deltares have acknowledged this gap. This problem was also observed by Knoeff et al. (2013), and mentioned by Van Mechelen (2013), Jongerius (2016) and Kentrop (2016). To address this, we developed a generic method to evaluate the reliability of multifunctional flood defenses.

This generic method identifies structural elements based on their contribution to the flood protecting function. First, the main function of a flood defense was subdivided into sub-functions. Second, structural element types were related to these sub-functions.

With help of a function analysis, we found that a flood defense needs to perform the following sub-functions:
To retain water
- to provide sufficient retaining height;
- to prevent water flowing through the flood defense;
- to prevent water flowing under the flood defense;
- to prevent water flowing around the flood defense.

To transfer the acting loads to the earth:
- to provide strength;
- to provide stability;
- to provide stiffness.

To resist all transferred external and internal loads.

These sub-functions were subsequently linked to the different structural elements that together compose flood defenses. Huis in 't Veld (1986) and Venmans (1992) also distinguished elements, but to develop this method, this was done more systematically. Seven types of elements were identified:
1. Water-retaining elements
2. Erosion-proof elements
3. Supporting elements
4. The subsoil
5. Objects
6. Transitions
7. Wave-damping elements

The way structural elements can be identified is demonstrated with the help of the hypothetical dike in Figure 1. This example contains all structural element types.

Figure 3. MFFD houses in Dordrecht, Netherlands (Photo courtesy Mark Voorendt).

Figure 4. MFFD quay in Hamburg, Germany. (Photo courtesy Mark Voorendt)

First, we try to identify water-retaining elements (type 1). The clay layer that seals off the sand core at the outer dike slope is an obvious water-retaining element. Another water-retaining element is the permanent flood wall in the form of sheet piles. In this example, the retaining wall is extended with an additional water-retaining element.

Next, we can look for erosion-proof elements (type 2). This is presumably present, since an outer slope of clay is usually protected by a separate layer. On the inner slope of a traditional sand dike, a clay layer often protects against erosion from overtopping waves.
In this example, the clay layer on the outer slope is additionally protected by concrete columns or blocks, which protect against erosion due to waves. The grass layer on the inner slope is also a type 2 element, because it protects against scour from overtopping waves or possible overflow. Another element that protects against erosion due to wave overtopping is the asphalt layer of the road on the crest of the dike. We do not find other elements that exclusively protect against erosion, but the flood wall combines this function with its primary function of retaining water.

Then, we look for type 3 elements, supporting elements. The clay layer is supported by the dike core, which is a typical type 3 element. The flood wall, already recognized as an erosion-proof water-retaining element, is also sufficiently strong and stable in combination with the counter-pressure of the soil in the dike core, so it also functions as a supporting element.

The subsoil bears the dike core including all external loads acting on it. This is the type 4 element.

Now, we can find three objects (type 5) in this example: a house in the dike, a sewage pipe in the dike, and a house next to the dike. These objects are considered to be part of a dike if they technically influence the functioning of the structure as a flood defense. In some cases, objects that were not originally part of a flood defense become part of it after future reinforcement (after the dike is widened, for example).

Transitions (type 6) are found for example at the interface of the house and the soil. It can, for instance, consist of a strip of asphalt mastic that prevents scour. Other transitions are the interface of the sheet pile flood wall and the revetment, the interface between the road and the dike cover (clay layer) and where slope angles change.

Finally, the outer berm is an example of a wave-damping element (type 7), reducing wave forces during extreme conditions; waves will break due to the shallowness created by the berm, which dissipates energy. This reduces overtopping volumes, which allows a lower crest height.

Using this 7-element model, we studied twenty-six different cross-sections of various flood defenses to verify whether the structural elements could be recognized in practice. These real cases were studied for two reasons:

- To check whether the method of distinguishing structural element types is applicable;
- To check whether the derived element types are generic.

The studied examples include typical monofunctional flood defenses, like sea dikes, river dikes and lake dikes, but also a dike coffer and an extendable flood wall. Multifunctional flood defenses were also studied, such as the Roof Park in Rotterdam (see pp. 166-183 in this volume), houses in Dordrecht (Figure 3) and a quay in Hamburg (Figure 4). A discharge sluice was analyzed as an example of a hydraulic structure, and a reservoir dam was taken as an example of an atypical form. This provided a comprehensive range of examples.

All element types could be recognized in these examples and no new types were found. The wide variety of structures that were studied assures that the distinguished structural element types are indeed generic. That means that flood defenses consist of two or more of these element types (a water-retaining element and the subsoil are always present).

The structural elements of flood defenses identified in this model are indeed generic and the method of identifying them is practical. Identifying the function(s) of structural elements gives insight into the consequences of different degrees of integration and different ways of combining the functions.
By relating these elements to failure mechanisms, a reliability analysis can be performed. This enables the over-all failure probability of multifunctional flood defenses to be calculated. This approach enhances the possibilities of expanding urban activities near flood defenses, while at the same time improving the flood protection level.