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# Structural evaluation of multifunctional flood defenses using generic element types

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## ABSTRACT

A lack of appropriate guidelines for the design and assessment hampers the development of multifunctional flood defenses like parking garages in quays and houses in dikes. The aim of the present paper, therefore, is to gain insight in the structural performance of multifunctional flood defenses and to provide a tool to evaluate design alternatives. For this purpose we have developed a generic method to determine the function of structural elements regarding flood protection. A study of diverse multifunctional flood defenses showed that the derived structural element types are indeed generic. We then applied the method to a real case, which showed that it factually provides more clarity and insight in the advantages and disadvantages of adding functions to flood defenses. This method will therefore advance the design and application of multifunctional flood defenses.

## INTRODUCTION

Due to continuously expanding urban activities and the need to improve the present flood 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 combined with quay walls, houses whose façades retain water and wind turbines on dikes. However, the present Dutch guidelines as well as the International Levee Handbook are not suitable to design or assess such these structures, which hampers their development and application.

The problem is that the present guidelines assume specific shapes of flood defenses, like gates or embankments, but multifunctional flood defenses, conversely, consist of atypical structural elements that require a different approach. The difficulty is the atypical combination of functions in the same structural elements: they could reinforce each other, but, which is worse, they could also create conflicts. Moreover, legal, governance and financial issues tend to impede integration of other functions in flood defenses.

In practice, many examples can be found of only partially integrated flood defenses, which is a result of avoiding conflicts instead of solving them. We mention a few examples:

- Düsseldorf (Germany): The tunnel parallel to the Rhine bank is not combined with the quay wall.
- Rotterdam (Netherlands): The dike next to the 'roof park' is structurally separated from the shopping/parking complex, although it visually looks integrated (see Figure 1).
- Katwijk aan Zee (Netherlands): A parking garage along the beach has not been integrated with a new sea dike, although some of the design alternatives (like in Figure 5) offered such a possibility.
- Tokyo (Japan): A floating barrier-wall protects a modern building front along the Sumida river, but this protection could have been integrated into the buildings themselves.

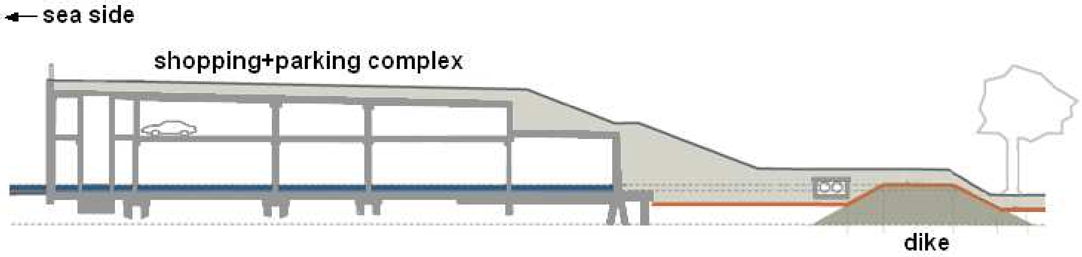

**Figure 1. 'Roof park' complex in Rotterdam (Van Veelen, 2015)**

The aim of this study is to gain insight in the structural performance of flood defenses and to evaluate design alternatives. For this purpose, this paper first develops a generic method to determine the function of structural elements regarding flood protection. We followed next steps to develop the method:

- A function analysis was used to divide the general main function of flood defenses, which is retaining water, into several sub-functions;
- The derived sub-functions were related to structural element types, so that these elements are defined by their structural function and not by specific shapes. These element types are therefore generic;
- A method of recognizing these functional elements was developed and many examples of flood defenses were studied to verify whether these functional elements can actually be recognized in practice.
- The method was then verified with help of twenty eight different real cases.

The method was then applied to a real case to test whether it creates better understanding of the structural performance of multifunctional flood defenses.

## THE METHOD TO DERIVE GENERIC STRUCTURAL ELEMENTS

### Deriving sub-functions

By definition, a flood defense protects land from being covered by water. Flood protection in practice means that the volume of water passing a flood defense is limited in order to reduce the consequences to acceptable levels. Sub-functions are now derived from this main function by considering the way in which water can flow across a flood defense. This is possible in only four ways: over, through, under, or around the structure (Figure 2):

1. The volume of water passing *over* the flood defense depends on the retaining height. The flood defense, which reaches up to this height, prevents overflow or wave-overtopping volumes higher than what is considered acceptable. This acceptability is judged considering the reliability and usability of the flood defense itself and the capacity of the protected area behind the flood defense;
2. The amount of water passing *through* the flood defense relates to the permeability of the material of which a flood defense is composed, or the cross-sectional area of the gates or other openings present in the flood defense;
3. The volume of water passing *under* a flood defense depends on the permeability of the subsoil and the interface between flood defense and subsoil;
4. The quantity of water passing *around* a flood defense can only be controlled if the flood defense entirely surrounds the area that has to be protected. The structural transitions between flood defense structures or segments should have the same volume-limiting functions as the adjacent flood defense sections or structures.

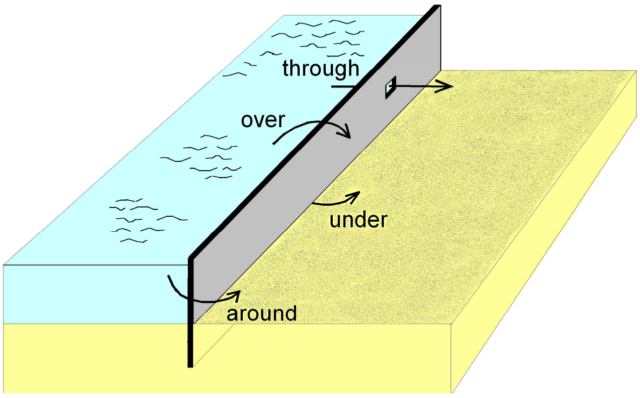

**Figure 2. Four ways in which water can flow across a flood defense (schematic)**

The four sub-functions that are directly related to the main function thus are: to prevent water flowing over, through, under, or around the structure in too high quantities.

We derived additional sub-functions regarding flood-protection from inherent structural integrity. The functioning of a structure in general, namely, depends on its ability to resist the acting loads. This means that a flood defense has to be sufficiently strong and stable, otherwise it will structurally fail. The strength of a material is its ability to resist the stresses working in that material. Strength can be attenuated by erosion or corrosion, or other mechanical or chemical effects. In case of repetitive loading and unloading, fatigue can affect the structural strength. Stability indicates the capability of a structure to maintain its shape and position. Strength and stability are needed to transfer the acting loads to the earth that finally has to resist all loads.

In addition, the stiffness of a structure is an important characteristic. Stiffness is less a relevant issue for embankments, but it is for slender walls, like sheet-pile walls. It is mainly relevant regarding usage (serviceability), which is mostly important for secondary functions of flood defenses. However, stiffness can also, indirectly, affect the structural integrity of the flood defense: In case of insufficient stiffness, a structural element could deflect in such a way that loads accumulate. The magnitude of these loads can become more than the structure is able to resist, so in that case, as a second order effect, these loads could exceed the strength.

To summarize, a flood defense performs the following sub-functions:

- to retain water:
    - To provide sufficient retaining height (overflow, overtopping);
    - To prevent water to flowing through the flood defense (permeability, area of openings);
    - To prevent water to flowing under the flood defense (transitions, permeability);
    - To prevent water to flowing around the flood defense (transitions, dike rings).
- to transfer the acting loads to the earth:
    - To provide strength;
    - To provide stability;
- to finally resist all transferred external and internal loads.

These sub-functions are generic, and therefore applicable to multifunctional defenses.

**Relating sub-functions to structural element types**

After deriving structural sub-functions from the main function of flood defenses, they were linked to types of structural elements that together compose flood defenses. Huis in ’t Veld et al. (1986), Venmans et al. (1992) and Voortman & Vrijling (2004) also distinguished element types, but in the present study they are related more systematically to sub-functions. This section identifies eight types of elements.

1. *Water-retaining elements*

Water-retaining elements serve the sub-functions of preventing water flowing *over* and *through* a flood defense. In fact, water-retaining elements can be fixed or moveable, but the movable water-retaining elements are separately denominated as ’closure means’ (see type number 5). Examples of fixed water-retaining elements are sheet-pile walls and possibly specific elements like façades of a house in a multifunctional flood defense. In sand dikes with a clay cover, the water-retaining elements consist of the clay cover together with the sand core and the subsoil. The permeability of the clay layer after all is just slightly less than the sand core, because of the presence of cracks and vegetation in the clay.

2. *Erosion-proof elements*
Water-retaining elements are directly exposed to water, so they can suffer from erosion by waves or currents, which could lead to failure of the water-retaining function. Protection against erosion is provided by erosion-proof elements, like a grass layer, or concrete blocks, on the outer slope of a dike. Elements that protect against *internal* (backward) erosion do not resort under this type, but are considered to be elements that provide stability (supporting elements).

3. *Supporting elements*
All loads on water-retaining elements have to be transferred to the earth. Added to the external loads are the loads coming from the flood defense itself (self-weight). This sub-function of transferring the loads to the subsoil is taken care of by supporting elements. These elements can only function if they are sufficiently strong and stable. Typical supporting elements are the core of a dike, and the structural frame and foundation piles of ’hard’ flood defense structures.

4. *The subsoil*
Preventing water flowing under a flood defense is covered by the subsoil: The subsoil should be sufficiently impermeable to prevent unacceptable volumes of water passing into the hinterland. The subsoil should also prevent failure of the defense due to this seepage flow. This kind of failure becomes a threat if seepage leads to internal backward erosion. The subsoil also resists all external and internal forces.

5. *Closure means*
Closure means are moveable water-retaining elements. These can be the gates in a navigation lock, a cut-off in a dike, the windows of a house and doors of integrated parking garages (if they are designed to retain water). Likewise, mobile barriers and emergency structures belong to the structural element type of closure means. We considered to include closure means in the type of water-retaining elements, but refrained from doing so, because the requirements regarding closure means are often stricter than for water-retaining elements.

6. *Secondary elements*
All structural elements that are somehow part of the flood defense *structure*, but not intended to contribute to the flood defense *function*, are considered to be ’secondary elements’. These elements serve other functions than flood protection and regarding this flood protection function, they only provide extra loads on structural elements that do contribute to fulfilling the flood defense function.

7. *Transitions*
Preventing water flowing around the flood defense structure is secured if the structures bordering in length-direction also retain water. To protect an area against floods, the flood defense structures (both artificial and natural) should namely form a continuous protective line, eventually in combination with higher land areas. Transitions in general mark a potential discontinuity in stiffness, roughness, structural coherence, or other material properties. They can also mark a change in geometry, like

the kink between the slope of a berm and the horizontal ground level. Transitions can also consist of discontinuities of structural elements to prevent too high material stresses in these elements, caused by changes in temperature or uneven settlements. These discontinuities tend to concentrate flow and can therefore induce physical processes that could lead to failure mechanisms like erosion and piping.

8. *Wave-damping elements*
Structural elements that intend to dissipate wave energy for the benefit of the flood defense are identified based on geometry, or material properties. This mainly concerns measures that dissipate the energy of the waves before they reach the crest of a flood defense. Forelands, dike berms, vegetation and moles (breakwaters) are good examples of wave-damping elements.

The procedure to recognize the different element types in a mono- or multifunctional flood defense starts with finding the structural part(s) that perform the water-retaining function. Then erosion-proof elements and supporting elements are searched for, followed by the sub-soil, secondary elements, transitions and wave-damping elements.

**Recognizing structural element types**
This section demonstrates the method of distinguishing structural elements with help of an imaginary, overtopping-resistant dike as depicted in Figure 3. This example contains all structural element types, except for type 5, ’closure means’.

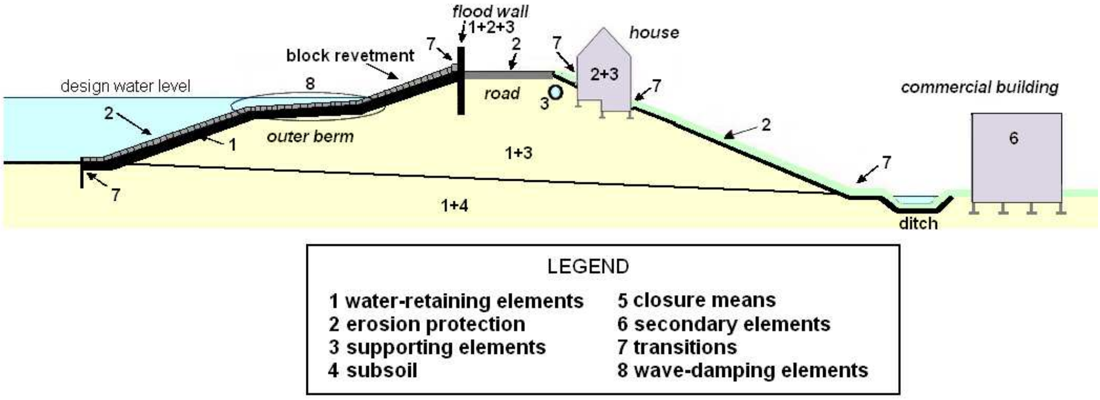

**Figure 3. Imaginary sea dike with structural elements**

First, water-retaining element(s) are identified (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 floodwall at the outer crest line, in the form of sheet-piles. It forms an additional water-retaining element, constructed as an improvement measure to increase the retaining height.

Consecutively, erosion-protective elements (type 2) are searched for. In this example it appears that concrete columns or blocks on the outer slope protect against erosion. On the inner slope, a clay layer with grass protects against erosion from overtopping waves. Another element that protects against erosion due to wave overtopping is the asphalt layer of the road on the crest of the dike. More exclusively erosion-protective elements are not present, but the floodwall combines this function with retaining water, and the house on the inner slope protects the core against erosion.

Then type 3 elements, supporting elements, are identified. The most obvious one is the dike core, which supports the water-retaining clay layer. Another one is the floodwall, which was already detected as an erosion-proof water-retaining element. The shallow-founded house on the inner slope is also a supporting element, because it partly replaces the dike core material in transferring the loads to the subsoil. Depending on the design specifications, the influence of the house on the stability of the dike could be positive or negative compared to the situation without the house. The same applies to the sewage pipe: it somehow influences the load transfer towards the subsoil.

The subsoil bears the dike core including all external loads acting on it. This is the type 4 element. Closure means, type 5, are not present in this example, but one secondary element (type 6) can be detected: a commercial building next to the dike. This element is considered to be part of a dike because it influences the stability of the inner slope if it is not too far from the dike. If it is located sufficiently far away from the dike, the building should not be identified as a secondary element, but as an external element (type 0).

A transition (type 7) can be found at the interface of the house on the dike and the grass layer. For instance, it can consist of a strip of asphalt mastic that prevents scour at this transition. Another transition is formed by the interface of the sheetpile floodwall and the revetment. The interface between the road and the dike cover (clay layer) is also a transitional element. Finally, the outer berm can be detected, an example of a wave-damping element (type 8) that reduces wave forces during extreme conditions, because waves will break due to the shallowness created by the berm, which dissipates energy. This reduces overtopping volumes, allowing a lower crest height.

### Relating structural elements to failure mechanisms

After relating all specific structural elements to functional element types, it can be checked whether the whole of these structural elements fulfills the requirements regarding flood protection (checking secondary functions is outside the scope of this research). This implies that it should be checked whether the flood defense directly or indirectly limits the amount of water passing the structures to acceptable quantities. Failure to fulfill this main function happens when somehow the loads exceed the resistance of the structure. This happens when one or more of its structural elements fail to fulfill their specific sub-function. Relating failure mechanisms to these structural elements is a task to be carried out by professional hydraulic engineers. The relations can be visualized in a diagram like Figure 4 (adapted from Huis in ’t Veld et al, 1986).

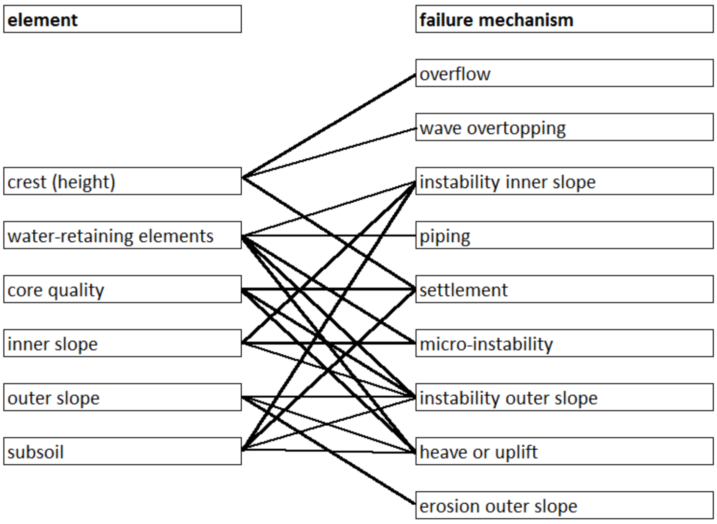

**Figure 4. Failure mechanisms related to structural elements**

The relation between failure mechanisms can then be schematized in a fault tree. This is a helpful tool to calculate the over-all failure probability of a flood defense (dike section) in a probabilistic way (see, for instance, the Fault Tree Handbook of NRC (1981) for a description of this method). Comparison of the over-all failure probability with the maximum allowed failure probability yields the reliability of the flood defense, which is the objective of this research.

## VERIFICATION

Until now, we described the method of finding structural element types with the help of an imaginary example. As a test, we applied this method to various real cases to assess its usability. We studied twenty-eight different cross-sections of various flood defenses to verify whether the structural elements could be recognized. The studied examples include typical coastal flood defenses, like German and Dutch sea dikes and a closure dam, but also multifunctional structures like a dike in a sea boulevard and a parking garaged combined with a sea dike. Overall, a broad range of examples was covered.

In principle, we were able to identify all element types and no new types showed up. The wide variety of studied structures assures that the distinguished structural element types are indeed generic. That means that flood defenses, in general, consist of one of more of these element types (a water-retaining element and the subsoil should always be present). Unfortunately, not in all cases the technical details were clear, so we had some difficulties in estimating the precise function of some structural elements. In these cases, we had to make assumptions, after which we after all were able to identify the element types.

## APPLICATION OF THE METHOD

We more extensively studied one of the alternative designs for the new multifunctional sea defense of Katwijk aan Zee, a coastal town in the Netherlands. Only a row of small dunes used to protect the town from storm surges. A dike protecting the further hinterland ran right through Katwijk, leaving the western part of the town unembanked. A new coastal defense therefore was needed to protect all residents. Researchers from TU Delft, TNO, Rotterdam's municipal engineering department, CUR building and infrastructure, and other agencies, made a design with a 15 to 20 meter deep diaphragm wall, which formed the main water-retaining element. They planned a parking garage behind that wall as a solution for the parking problems during the tourist season. Figure 5 shows a cross-section, including an indication of structural element types.

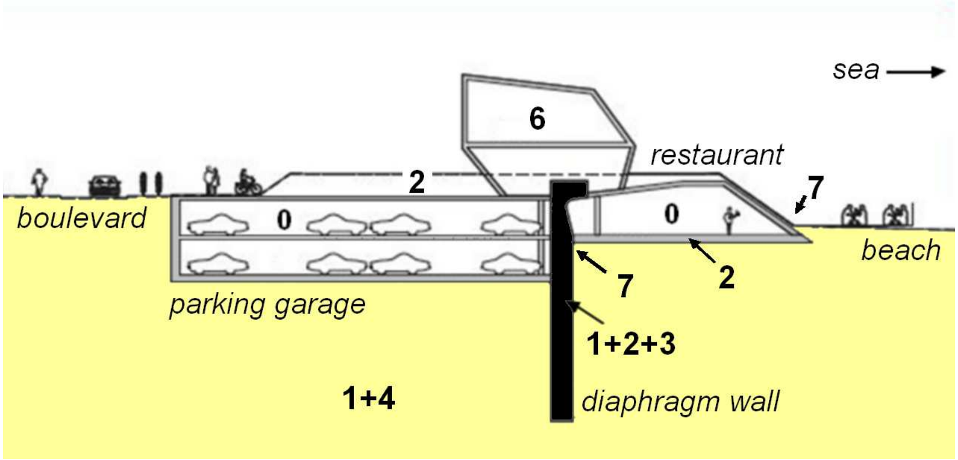

**Figure 5. Cross-section of the wall-in-dune alternative for Katwijk, Netherlands**

To prevent failure, all elements should be sufficiently reliable. The diaphragm wall, to start with, should be sufficiently strong and stable. Strength is provided by the concrete quality, wall thickness, steel reinforcement and stability by the embedded depth. There are no additional elements needed to support the diaphragm wall; only the subsoil should have sufficient bearing capacity to resist all forces acting on the structure during design conditions.

The structure is designed in such a way that the wall still fulfills its flood-protection function after erosion of the beach during a design storm. A 25 meter wide revetment, which also serves as the floor of the lower restaurant, prevents scour in front of the wall: Collapse of the restaurant would only cause minor local damage but would not affect the diaphragm wall. Part of the garage roof just behind the wall protects against erosion due to possible overtopping waves.

The restaurant structure on the beach side of the wall can be considered non-existing regarding the flood-protection function of the structure, except for the floor that protects against scour. The restaurant on top of the wall acts as an extra load on the wall, which should be taken into account in the structural design of the diaphragm wall. The parking garage protects the dunes behind the diaphragm wall against erosion by overtopping waves.

Relevant transitions are the interfaces in between the beach and the bed protection (restaurant floor) and in between the bed protection and the diaphragm wall. Other transitions in cross-direction are not critical, because the wall on itself should be able to provide sufficient strength and stability, next to the additional bed protection.

The gentle slope of the beach dampens the waves. The presence of sufficient sand in the transects should be monitored regularly. When this volume appears to be insufficient, the beach will need to be nourished again.

The functions of the structural elements regarding flood protection are known now, so it can be now be endeavored to link these elements to failure mechanisms. The result is shown in Figure 6. One should realize that included secondary elements, like the garage roof, should meet requirements related to flood protection as well as to the parking.

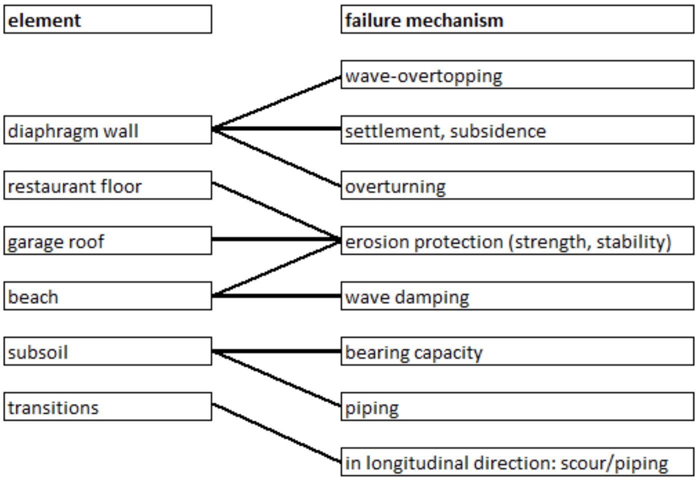

**Figure 6. Structural elements and failure mechanisms for the wall-in-dune design in Katwijk, Netherlands**

A fault tree can now be devised with help of limit-state functions and in this way the overall failure probability of the flood defense can be estimated.

Because the structural functions of the elements are known now, also the degree of spatial integration can be determined. Van Veelen et al (2015) indicate some categories of spatial and structural integration. In this example, functions appear to be integrated into one structural element ('functional integration'), because the water-retaining diaphragm wall also serves as back wall of the restaurant and parking garage. However, the parking garage could also have served as a support for the diaphragm wall, which is schematically indicated in Figure 7 (with raking piles). This would result in a more slender diaphragm wall with less embedded depth compared to the original design.

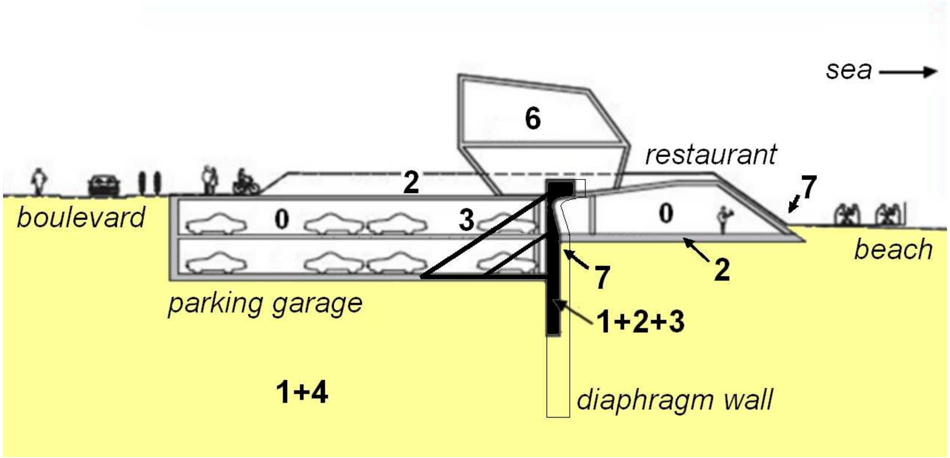

**Figure 7. Improved design of the wall-in-dune alternative in Katwijk**

## DISCUSSION AND CONCLUSIONS

In this paper, we developed a typology of structural elements in flood defenses. While verifying the method, we made some observations:

- Water-retaining elements always appear to fulfil two sub-functions, namely preventing water flowing over and flowing through a flood defense. It is nevertheless important to distinguish the two functions of the retaining element, because these functions entail different kinds of requirements. This distinction is relevant for the reliability evaluation of flood defenses.
- Structural elements can have different roles during consecutive life stages, like construction and usage. The function, or required geometry, of an element thus can change per stage. This certainly has to be taken into account when making a structural evaluation.
- The exact division line between supporting soil bodies and the subsoil is sometimes hard to draw, because at forehand it is difficult to estimate the exact sliding planes. Even calculation methods, like those developed by Bishop and Rankine, only offer approximations. However, we expect that this will not hamper the development of an assessment method for multifunctional flood defenses, because the current design practice deals quite well with it.
- In some cases, secondary elements can originally not be part of a flood defense, but will become part of it after future reinforcement (after widening of a dike, for example).
- Longitudinal cross-sections are hardly available. This could be a cause of the neglect of transitions in this direction, which could explain some observed failures of flood defenses.

Over-all it can be concluded that the typology appears to be generic indeed, because it is based on a function analysis rather than on traditional forms. It gives insight in the consequences of combining functions in structural elements and the functioning of a multifunctional flood defense as a whole. It also facilitates the generation and evaluation of different structural design alternatives. It can, for example, be decided to assign different consequence classes (and according safety margin) or design life time to structural elements. It can be used to evaluate the structural reliability of multifunctional flood defenses.

The method is also helpful in understanding the consequences of changing urban functions in combination with the more permanent flood defense function (adaptability). In addition, it is useful for developing strategies for inspection, assessment and maintenance of multifunctional flood defenses and in that way contribute to solving governance and legal issues related to implementing multifunctional flood defenses.

## ACKNOWLEDGEMENT

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