Realistic Modelling of External Flooding Scenarios
A Multi-Disciplinary Approach

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Abstract: Extreme phenomena, such as storm surges or high river water levels, may endanger the safety of nuclear power plants (NPPs) by inundation of the plant site with subsequent damage on safety-related buildings. Flooding may result in simultaneous failures of safety-related components, such as service water pumps and electrical equipment. In addition, the accessibility of the plant may be impeded due to flooding the plant environment. Therefore, (re)assessments of flood risk and flood protection measures should be based on accurate state-of-the-art methods.

The Dutch nuclear regulations require that a nuclear power plant shall withstand all external initiating events with a return period not exceeding one million years. For external flooding, this requirement is the basis of the so-called nuclear design level (Nucleair Ontwerp Peil, NOP) of the buildings, i.e. the water level at which a system – among others, the nuclear island and the ultimate heat sink – should still function properly. In determining the NOP, the mean water level, wave height and wave behaviour during storm surges are taken into account. This concept could also be used to implement external flooding in a PSA, by assuming that floods exceeding NOP levels directly lead to core damage. However, this straightforward modelling ignores some important aspects: the first is the mitigative effect of the external flood protection as dikes or dunes; the second aspect is that although water levels lower than NOP will not directly lead to core damage, they could do so indirectly as a result of combinations of system loss by flooding and random failure of required safety systems to bring the plant in a safe, stable state. A third aspect is time: failure mechanisms need time to develop and time (via duration of the flood) determines the amount of water on site.

This paper describes a PSA approach that takes the (structural) reliability of the external defences against flooding and timing of the events into account as basis for the development and screening of flooding scenarios.:

Keywords: PRA, Hazards, External Flooding, Modelling.

1. INTRODUCTION

Extreme phenomena, such as storm surges or high river water levels, may endanger the safety of nuclear power plants (NPPs) by inundation of the plant site with subsequent damage to safety-related buildings. Flooding may result in simultaneous failures of safety-related components, such as service water pumps and electrical equipment. In addition, the accessibility of the plant may be impeded due to flooding of the plant environment. These consequences are so severe that, (re)assessments of flood risk and flood protection measures should be based on accurate state-of-the-art methods.

Dutch nuclear regulations require that a nuclear power plant shall withstand all external initiating events with a return period lower than one million years. For external flooding, this requirement is the basis of the so-called *nuclear design level* (nucleair ontwerp peil, NOP) of the buildings for external flooding, i.e. the water level at which a system – among others, the nuclear island and the ultimate heat sink – should still function properly. In determining the NOP, the mean water level, wave height and

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wave behaviour during storm surges are taken into account. This concept could also be used to implement external flooding in a PSA, by assuming that floods exceeding NOP levels directly lead to core damage. However, this straightforward modelling ignores some important aspects: the first is the mitigating effect of the external flood protection as dikes or dunes; the second aspect is that although water levels lower than NOP will not directly lead to core damage, they could do so indirectly as a result of combinations of system loss by flooding and random failure of required safety systems that have to bring the plant in a safe, stable state. Time is a third ignored aspect: failure mechanisms need time to develop and time (via duration of the flood) determines the amount of water on site.

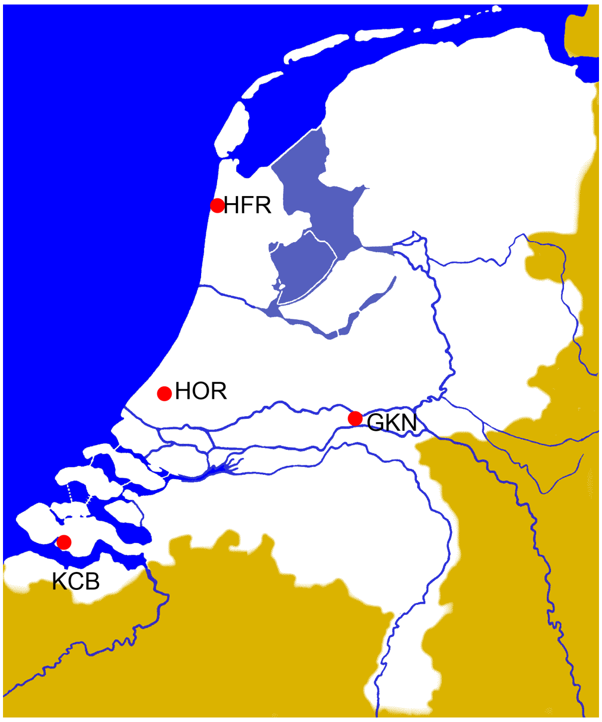
This paper describes a PSA approach that takes the (structural) reliability of the external defences against flooding and timing of the events into account as basis for the development, screening and quantification of flooding scenarios.

2. SITES IN THE NETHERLANDS

In the Netherlands there are four sites where nuclear reactors were or are located. Figure 1 gives their locations. The first nuclear power plant built in the Netherlands was a 50 MW_e BWR (GKN, a pre MK I with two suppression tanks). This plant – shut down since 1997 - was located in the floodplains of the river Waal. The second power plant is located close at the North Sea coast in the Westerschelde estuary: KCB 500 MW_e PWR. The third and fourth reactors are pool type research reactors built in the early 60-ties of the last century. The smallest one (HOR: 3 MW_{th}) is located several meters below sea level in a polder area near the city of Delft and the other (HFR: 45 MW_{th}) is located in the dunes in the North West part of the Netherlands.

Given their location, it will be clear that all 4 plants needed to consider external flooding as part of the design basis and later in their PSA. The four site locations illustrate the fact that external flooding is site specific. River floods differ in height and duration from sea floods, river dikes fail differently compared to sea dikes, dunes in their turn fail in a different way compared to dikes. In case of sea flooding the impact of waves has to be assessed. In river flooding waves play a minor rule.

Figure 1: Sites of Nuclear Reactors.



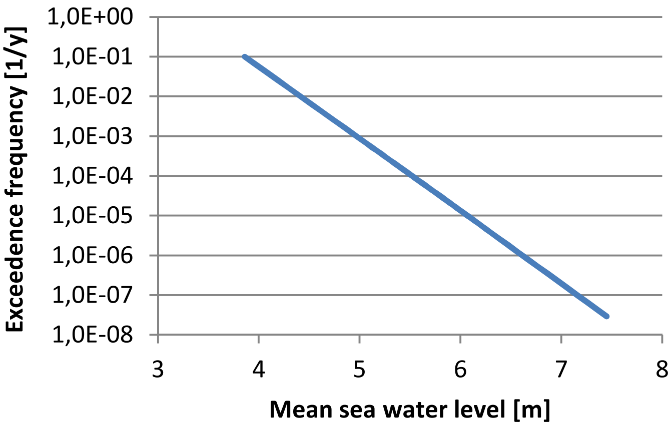
3. DETERMINISTIC DESIGN

3.1 Nuclear Base level

In 1980, the Nuclear Base Level (in Dutch: Nucleair BasisPeil, NBP) and the Nuclear Design Level (Nucleair Ontwerp Peil, NOP) were introduced. The NBP results from the requirement that a nuclear power plant should be protected against external hazards in such a way that the probability of an accident with serious consequences caused by external events - in this case floods-, will be small compared to the risk of serious accidents originating from causes within the plant itself. This requirement is met if the safety measures are such that an external event with a return period of 1 million years (frequency of 1E-6 per year) or more can be withstood.

Basis of the NBP assessment is the official Water Level Exceedence Frequency line as used by the authorities in the design of the Dutch flooding defences. Figure 2 gives an example for a sea location at the west coast.

Figure 2: Water Level Exceedence Curve



3.2. Nuclear Design Level

The next step is to add various surcharges to the NBP, as defined in the regulations of the IAEA. The resulting level is the calculated nuclear design level (calculated NOP). Examples of surcharges to take into account are:

- Effects of showers;
- Compensation for rising sea level and decreasing soil level;
- Building settlement;
- Wave height.

Because of the dynamic effects of the water (waves), the calculated NOP can be distinguished in:

- **Static NOP** The level at which a constant water load acts on the walls of the buildings in which the safety-related systems and components are housed. This water level is used in the stress - strength calculations for the building design, to withstand the water pressure.

- **Dynamic NOP** This level takes the wave action into account and is used to determine the minimum elevation at which systems have to be placed or to which height buildings should be water tight.

The expected life time of the plant has to be taken into account when calculating the surcharges for Building settlement and rising sea water level. Regarding of safety functions, the calculated dynamic NOP is decisive.

4. PSA

4.1. PSA and NBP

This NOP concept, as it has a frequency base, could also be used to implement external flooding in a PSA, by assuming that floods exceeding NOP levels directly lead to core damage. However, as mentioned earlier, this straightforward modelling ignores three important aspects: the first is the mitigating effect of the external flood defences protecting the plant; the second aspect is that although water levels lower than NOP will not directly lead to core damage, they could do so indirectly as a result of combinations of system loss by flooding and random failure of required safety systems to bring the plant in a safe, stable state, and thirdly, the time aspect is ignored in two ways: 1) failure mechanisms need time to develop and 2) time (via duration of the flood) determines the amount of water on site. Consequently, a more sophisticated approach is needed. In the development of this approach, use is made of the work of the Netherlands' Department of Water Management (Rijkswaterstaat), which applies a comparable probabilistic method for evaluating the designs of new and existing dikes and dunes.

From the three aspects mentioned above, it is clear that the change in approach is not so much in the flooding scenario development and modelling, but rather in the way the initiating event: the relation between water levels outside the external flooding defences and the water levels on site or in the plant buildings. This relationship is as well physical (water level) as numerical (frequency).

4.2 Flooding scenario's

The development of external flooding scenarios in event trees starts with establishing which water levels will impact the safety relevant structures, systems and components, e.g. what on site water level causes loss of off-site power, what level loss of the secondary plant. Loss can simply be caused by inundation of components or by collapse of a building. In the first case the static water level inside the building is determining. In the latter case not only direct (dynamic) forces from the water on the walls of the buildings have to be taken into account, but also - depending on the distance between building and the point where the water is entering the plant site – undermining phenomena of the foundations need attention. With respect to waves, one should bear in mind that the wave height after the breach is far less than for instance at sea, as long as the water is flowing fast through the breach. The plant internal design features against external flooding play a dominant role.

Once the discrete water levels are established, the scenario development is – as with all hazards – in principle straight forward. The basis of the event trees describing the flooding scenarios is the PSA internal events model. In general the event trees for a normal plant trip, loss of off-site power and loss off ultimate heat sink are used. These trees are pruned or modified to account for (part of) systems lost as result of the flooding level.

Before any external flooding scenario (event tree) can be developed, the relationship between water level outside the defences against flooding and the water level and thus consequences inside the plant should be clear. In fact the reasoning starts backwards as compared to the scenario description given by the event tree: what are critical flooding levels inside or onsite around the plant that impact safety relevant structures, systems and components and how can those levels be related to water levels in the river or at sea. In general this will not be a one to one relationship.

4.3. Flooding frequencies

Generally less straight forward is determining the initiating event frequencies for floods that should be taken into account in the PSA model. This requires some sort of translation from the water levels off-site to the critical water levels on site. Two issues influence this translation:

1. The conditional failure probability of the external flood defence.

2. The duration of the flood in combination with the flood height, the way the flood defence fails and the site characteristics: a) the height of the site as compared to the sea and to its surrounding area and b) the area that can flooded. These parameters determine the water level that is reached behind the failed flood defence.

Both issues lead to a reduction of the initiating frequency. The first issue results in a reduction factor on the initiating frequency at a given water level. The second issue makes that a higher water level (with a lower frequency) is needed off-site to obtain a certain water level on site. The next paragraphs will elaborate this.

4.3.1. Failure of dikes and dunes

Flood defences can fail in different ways. Although it looks like the most obvious mechanism overtopping is not the only and also not per definition the dominant failure mechanism of a flooding defence. Figure 3 gives an overview of the main failure mechanisms of dikes and dunes:

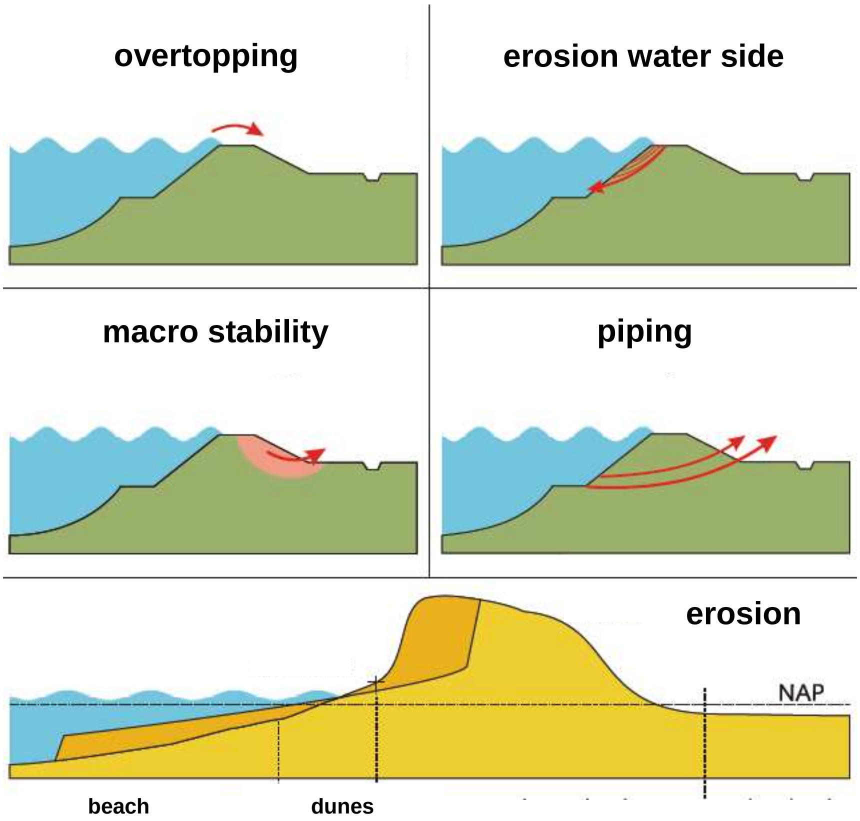
- **Overtopping**
  In this case the dike fails because large amounts of water overrun the dike; the dike is simply not high enough;
- **Macro-stability**
  The dike becomes unstable by water penetrating and saturating the core of the dike. As a consequence the inside slope of the dike starts sliding under the sea or river side water pressure;
- **Sea side erosion**
  The top layer (grass plus clay, stone, tarmac) is damaged by wave attack. Once this protective top layer is gone the main dike structures are eroded away.
- **Piping**
  The water pressure forces water under the clay layer that covers the main structure of the dike or under the clay layer that forms its foundation. So called pipes form and the sand in or under the dike is washed away causing the dike to collapse. Piping also plays a major role where for instance the pipework of the ultimate heat sink penetrates the dike and no design precautions e.g. in the form of addition screens, are taken to counteract this mechanism.
- **Erosion of dunes**
  Dunes fail in general simply by the wave action of the sea. Every wave reaching the dune row erodes the dune by removing sand. The erosion speed is influenced by the length and slope of the beach in front of the dunes.

From the description of the possible failure mechanisms it will be clear that flood defences can and will fail at water levels below their maximum height; e.g. before overtopping becomes the dominant failure mechanism.

When trying to quantify the probability of failure a definition of what a failed defence is, is necessary. In all cases failure is defined as the condition that the amount of water passing the flood defence exceeds a predefined amount. Before this amount is reached the water that passes the flood defence will not lead to problems behind the defence. For a dike for instance it signifies the starting point of the development of a breach. From this point on it will take time to develop a full size breach.

To obtain the (conditional) failure probability the structural reliability of the flood defence is calculated by evaluating the resistance of the flooding defence against the possible failure mechanisms (being the strength of the flood defence) initiated by the high tide (being the stress on the flood defence). Interactions between the different failure modes are taken into account. Parameters influencing the strength of the flooding defence are the dimensions (e.g. width, height, the inside and outside slope of dike), the material used for the underground, the core, and top layer (clay) and cover (grass, tarmac, cobbles, stone), density and grain size distribution of the sand and clay, permeability, subsoil type etc. For dunes and sea dikes the slope of the sea bottom and the width of the beach play an important role. Mean water level, wave height, wave frequency and wave direction are factors that determine the stress.

Figure 3: Major Failure Mechanisms for Dikes and Dunes [1].



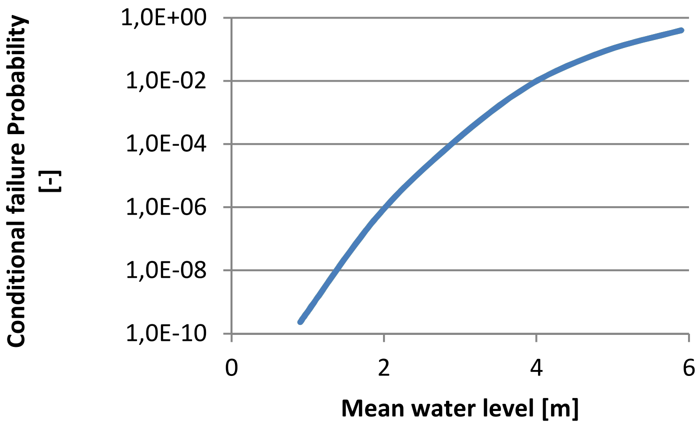
In table 1 an example of the output of the calculation for a section of a sea dike at a given storm surge level is presented. It shows that erosion of the outer slope at the locations with a grass cover dominate the probability of failure. Overtopping is not a major concern. Which of the mechanisms is dominant, changes with the water level. It will be clear that overtopping will become more and more dominant when the water level comes nearer to the height of the dike. Also the type of flooding influences the dominant failure mechanism. In case of river dikes the stability of the dikes is a major concern, Piping and macro-instability are in general the dominating failure mechanisms. There will in general be less dynamic attack by waves, but the much longer time water will stand against the dike, as compared to high water levels at sea, can cause saturation of the core of the dike and thus instability and the one sided water pressure promotes piping..

Table 1: Example of a conditional failure probability, total and per failure mechanism, for a flooding height of 2.9 m.

Failure mechanism	Failure Prob.	Combined Failure Prob.
Overtopping	2.9E-08	9.9E-07
Sea side erosion: stone cover	8.6E-10	
Sea side erosion: grass cover	9.4E-07	
Piping	1.2E-08	
Macro stability	1.3E-08	

Figure 4 gives a result of a complete set of stress strength evaluations of a dike section over a range of water levels for an example river dike. As expected the conditional failure probability is very low for normal water levels between 0 and 2m above the local reference level. It approaches unity when the water level tends towards the maximum height of the dike (6.3m).

Figure 4: Conditional failure probability of a dike as function of flood level [m above reference level]



4.3.2 Water level on site

The water level on site is determined by two factors: the amount of water that can enter the site through the breach and the amount of water that is needed to reach a certain water level on site.

Breach calculations

The amount of water that can enter the site is depending on the duration of the high water level, and the size of the breach. High water levels in a river caused by for instance melting snow or heavy or prolonged rain can last for a long time (several days to over a week), while high flood levels on sea are mostly limited by the duration of the storm and the normal tide (12 - 48 hours). Also the breach size and thus the amount of water that can enter the site is a function of time. Time is needed for the process of developing a breach and for the growth process of a breach.

Erosion starts - for instance, depending on the dominant failure mechanism - at the inner slope by the small amounts of water that are flowing down. The inner slope will erode until the crown of the dike is reached. The amount of water entering the site will remain small and constant until the crown of the dike is completely eroded away and the height of the dike starts dropping and the breach starts growing in width. This growth will stop when the flow rate of water through the breach is so low that no further erosion is possible [2].

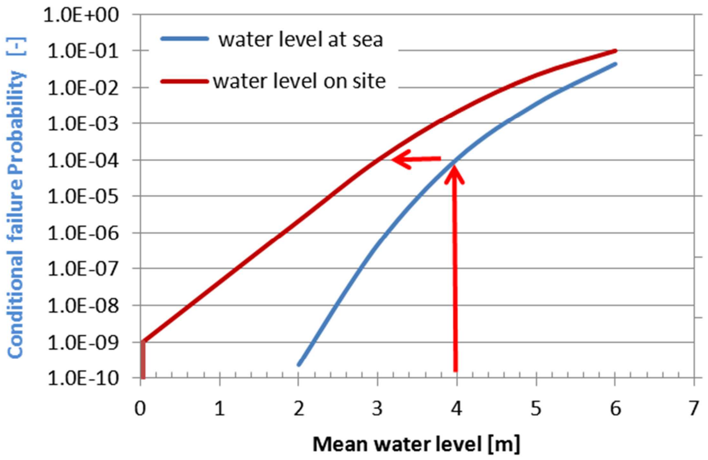
As this process takes time and the speed it develops increases with increasing water level, it is imaginable that - certainly at lower flood levels at sea - the breach has no time to develop fully before the flooding level at sea drops. This means that although the flooding defence has failed no water will enter the site.

Basin calculations

If a full breach develops, the next step is to evaluate the resulting water level on site taking into account the surroundings of the site. Factors to consider are the size of the area that is open to flooding, its elevation with respect to the normal mean sea level, secondary flood defences, and the height differences within the flood threatened area. Also in this case it is possible that flooding levels will be very limited, as the amount of water available could limited in relation to the available area.

An example result of such an evaluation (from breach and basin calculations) is given in figure 5. For instance a flood level outside of the flood defences (blue line) of 4 m corresponds with a water level on site of approximately 2.8 m (red line). The corresponding conditional probability of the flood defence failing at these levels is 1E-4. Outside flood levels below approximately 2.1 m do not result in significant amounts of water on site, because although the flood defence fails, this relatively low water level has no potential to form a breach of any significance.

Figure 5: Relation between water level on site (red line), and the flood level (blue line)



4.3.3. Initiating event calculation

The last step in the process is to obtain the initiating event frequencies for identified threatening water levels on site (plant flooding scenarios). This is done by combining the conditional failure probability given a certain water level on site from figure 5 with the exceedence frequency from figure 2.

The process is illustrated in the two figures below. Suppose the following flooding scenario: off-site power is lost at a water level of 3m on-site (red arrows in figure 6) and that additional systems fail at 4.4m on-site (green arrows in figure 6). The loss off-site power situation then exists between off site water levels of 4 and 5.1 m with a conditional probability of failure of the dike varying between approximately 1E-4 and 7E-3. The accompanying exceedence frequencies lie roughly between 5E-2 and 5E-4 (red and green arrows in figure 7).

Figure 6: Relation water level on site and the flood level: red arrows: start of flooding scenario, green arrows end of scenario

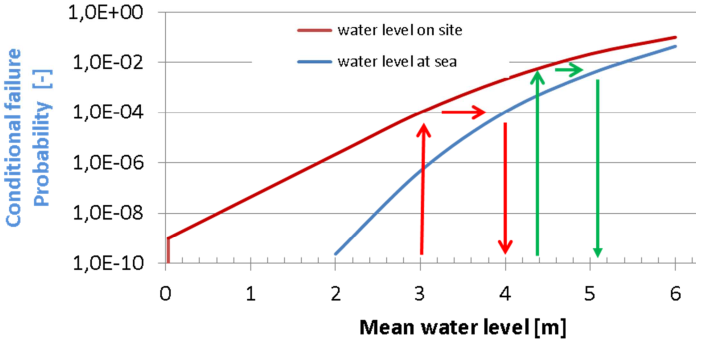
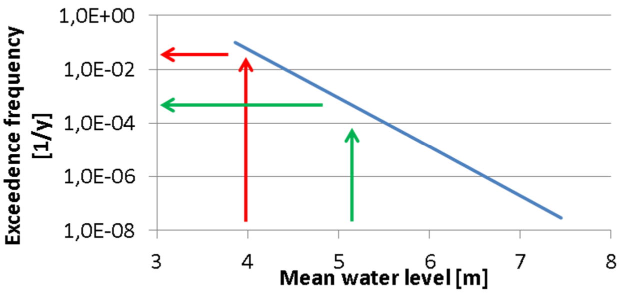


Figure 7: Exceedence frequency: red arrows: start of scenario, green arrows end of scenario



The resulting initiating frequency for loss of off-site power due to flooding is approximately 2.3E-5 per year. This value is calculated by discretising the exceedence curve between 4m and 4.8m resulting in an approximated frequency per water level, multiplying these frequencies with their the corresponding conditional failure probabilities and summing the results. This process is illustrated in table 2.

Table 2: Initiating frequency of LOSP scenario caused by external flooding

Event	Water level in plant [m]	Water level at sea [m]	Exceedence frequency [1/y]	Frequency [1/y]	Cond. prob. of dike failure [-]	Initiating frequency [1/y]
start of LOSP	3	4	0,0524	0,0179	0,0001	1,9E-06
		4,1	0,0345	0,0118	0,0002	2,0E-06
		4,2	0,0227	0,0078	0,0003	2,1E-06
		4,3	0,0149	0,0051	0,0004	2,1E-06
		4,4	0,0098	0,0034	0,0006	2,1E-06
		4,5	0,0064	0,0022	0,0010	2,2E-06
		4,6	0,0042	0,0015	0,0015	2,1E-06
		4,7	0,0028	0,0010	0,0022	2,1E-06
		4,8	0,0018	0,0006	0,0033	2,1E-06
		4,9	0,0012	0,0004	0,0048	2,0E-06
		5	0,0008	0,0003	0,0071	1,9E-06
additional failures	4,4	5,1	0,0005			
				Initiating frequency LOSP scenario due to flooding		**2,3E-05**

6. PRACTICAL EXPERIENCE

The method has been applied in updating an existing external flooding analysis and in the development of a new analysis. For the existing analysis, the frequency of identified flooding scenarios of the plant turned out to be significantly lower than in the previous study. The decrease has to main reasons. The main reason is the calculated difference between the water level at sea and the water level on site. The former model assumed the same water level off-site and on-site in case of a breach of the flood defences. An additional insight gained from the breach and basin calculations made for this study was that the wave height on site was much lower than originally assumed. The effect of the lower waves is that a higher water level on site is needed to cause a specific scenario to happen. The higher water on site results in a required higher water level on sea with a corresponding lower frequency.

In case of the new study for the second site, the results of the structural reliability analyses of the flood defences show that the rows of dunes in front of the plant have a failure frequency that is below 1E-8 per year. Two weak spots with a much higher frequency have been identified north (approximate distance 3 km) and south (1km) of the plant. The water might then reach the plant through the valleys between the dunes. Preliminary flow path analysis based on detailed contour maps of the area that are publicly available [3] show that the water will probably not reach the plant, because the water will be diverted to the hinterland through low spots in the last dune row. These spots have a height that is lower that the minimum plant elevation.

7. CONCLUSIONS

Realistic modelling of external flooding scenarios in a PSA requires a multi-disciplinary approach. Next to being thoroughly familiar with the design features of the plant against flooding, like its critical elevations for safety (related) equipment and the strength and stability of buildings, additional knowledge is necessary on design of flood protection measures as dikes and dunes, their failure behaviour and the modelling of this failure behaviour.

The approach does not change the basic flooding scenarios – the event tree structure – itself, but impacts the initiating event of the specific flooding scenarios and results more realistic and better underpinned initiating event frequencies.

References

[1] http://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma%27-projecten/veiligheid-nederland/publicaties/illustratiemiddelen/

[2] P.J. Visser, Breach growth in sand-dikes, doctoral dissertation, Delft University of Technology, 1998, Delft.”

[3] www.ahn.nl