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## **Risk Assessment for Flanders - Comrisk Subproject 6**

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# Risk Assessment for Flanders

## COMRISK Subproject 6

TOON VERWAEST, KOEN TROUW

### S u m m a r y

The coastal lowlands of the Belgian region Vlaanderen and the Dutch region Zeeuws-Vlaanderen constitute one cross-border flood unit. If a dike breaches in the Dutch part of this flood unit, the water might well flow into Belgium and vice versa.

This paper presents the results of a case study of calculation of coastal flooding risk for a cross-border coastal flood unit from Zeebrugge in Belgium (Vlaanderen) to Breskens in the Netherlands (Zeeuws-Vlaanderen), abbreviated within the COMRISK project as the „Flanders“ case study area. The goal of the study was to investigate how good a flood risk assessment can be done with state of the art knowledge. The approach chosen was to do a case study with the available risk assessment methods and to evaluate the effects of the different sources of uncertainties by means of a sensitivity analysis.

Hydrometeorological boundary conditions characterising extreme storm events were analysed. The return period of an extreme storm resulting in serious flooding is of the order of magnitude of 1.000 years or more, whereas data of hydrometeorological characteristics of storms are limited to a series of less than 100 years. Therefore a very large uncertainty exists on the expected return period of extreme storm events causing serious flooding. The storm surge level of an extreme storm event is the most determining storm characteristic with respect to the associated flooding. Wave characteristics are also important, but found to be relatively well correlated with the storm surge level.

Different modes of failure of the sea defences were investigated. The most relevant in this case were erosion of beaches in front of sea defence structures followed by instabilities of parts of these structures due to wave attack and/or overtopping, followed by erosion of the core of these structures until breaching. Dune erosion was also investigated. Where dunes still exist as the natural sea defences no breaching occurred.

Flood modeling results were sensitive to the various estimates made for breach growth, in depth as well as in width. Stability of the secondary dikes existing in some parts of the coastal plain was assumed. With or without temporary blocking of the flooding propagation by secondary dikes the model results showed that the more distant parts of the coastal plain were not flooded.

As consequences of a flooding event direct economic damage and human casualties were calculated on a GIS-based approach. Thus significant consequences are not taken into account, e.g., damage to nature, psychological damage, damage to the economy outside the flooded area.

For a series of return periods (1,000 years, 4,000 years, 10,000 years and 40,000 years) expected values of the consequences were calculated. The annual risk was calculated as a sum of the probabilities times the consequences. The propagation of the different sources of uncertainties results in an uncertainty with a standard deviation of a factor 10 (order of magnitude) on the annual risk.

It is concluded that, on the one hand, further research is essential to reduce the very large uncertainty on the results. Research is most needed on the failure behaviour of the sea defences in the time domain (beach erosion, initiation of damage, breaching, breach growth...). On the other hand, the risk calculations that are feasible at present, with very limited accuracies, are nevertheless very useful for coastal defence management actions like informing the public, defining research priorities, comparing the relative importance of measures and defences, and elaborating contingency plans for possible scenarios of breaching of defences.

## Zusammenfassung

*Die Küstenniederungen in der belgischen Region Vlaanderen und der niederländischen Region Zeeuws-Vlaanderen stellen einen grenzüberschreitenden Flutraum dar. Wenn ein Deich im niederländischen Teil bricht wird das Wasser auch in Belgien einströmen und vice versa.*

*In diesem Beitrag werden die Resultate einer Fallstudie zur Berechnung der Überflutungsriskiken für einen grenzüberschreitenden Flutraum von Zeebrugge in Belgien bis Breskens in den Niederlanden dargestellt, die sog. Fallstudie Flanders. Ziel war es zu untersuchen, inwieweit mit dem heutigen Kenntnisstand eine Risikoermittlung durchgeführt werden kann. Mit den heute verfügbaren Methoden wurde das Risiko ermittelt und die Auswirkungen der verschiedenen Quellen für Unsicherheiten mittels einer Sensitivitätsanalyse bewertet.*

*Hydrometeorologische Rahmenbedingungen für Extremereignisse wurden analysiert. Der Wiederkehrintervall für Extremereignisse die zu einer Überflutung führen liegt bei 1,000 Jahren und mehr, während die entsprechenden Datenbestände weniger als 100 Jahre lang sind. Daher existiert eine große Unsicherheit hinsichtlich der Wiederkehrintervalle für Überflutungsereignisse. Der Sturmwasserstand ist der bestimmende Parameter hinsichtlich der Überflutung. Auch Wellenparameter sind signifikant, aber korrelieren relativ gut zu den Sturmwasserständen.*

*Verschiedene Versagensmechanismen wurden untersucht. Der relevanteste Mechanismus war die Erosion der Strände vor Schutzwerken, gefolgt durch Erosion des Kernes dieser Schutzwerke bis zum Versagen (Durchbrechen). Dünenerosion wurde ebenfalls untersucht. Dort, wo Dünen als natürlicher Schutz noch vorhanden sind trat kein Versagen auf.*

*Die Resultate der Überflutungssimulation reagierten empfindlich auf die verschiedenen Annahmen für die Bruchentwicklung, sowohl in der Breite wie in der Tiefe. Die Standfestigkeit von vorhandenen zweiten Deichlinien wurde angenommen. Mit oder ohne zeitliche Blockierung der Flutwelle durch zweite Deichlinien zeigten die Simulationen, dass die küstenfernen Regionen nicht überflutet wurden.*

*Die aus einer Überflutung resultierenden direkten wirtschaftlichen Schäden und Menschenverluste wurden GIS-gestützt ermittelt. Signifikante Schadenskategorien wie Schäden an der Natur, psychologische Schäden und indirekte wirtschaftliche Schäden außerhalb des überfluteten Raumes wurden nicht berücksichtigt.*

*Für verschiedene Wiederkehrintervalle (1.000, 4.000, 10.000 und 40.000 Jahre) wurden die Werte ermittelt. Das jährliche Risiko wurde berechnet als das Produkt aus der Summe der Versagenswahrscheinlichkeiten und der Konsequenzen (Schäden). Die Fehlerfortpflanzung der verschiedenen Unsicherheitsfaktoren resultiert in einem Faktor 10 für die Standardabweichung (Größenordnung 10) für das jährliche Risiko.*

*Es wird gefolgert, dass weitere Forschung unabdingbar ist um die sehr großen Unsicherheiten zu reduzieren. Forschungsbedarf besteht insbesondere beim zeitlichen Versagensverhalten der Schutzwerke (Stranderosion, Schadensinitüierung am Bauwerk, Bruchentstehung und -Entwicklung). Trotzdem sind die Risikoermittlungen mit den bestehenden Unsicherheiten von großem Wert für Bestandteile eines Risikomanagements wie die Information der Öffentlichkeit, die Definition von Forschungsprioritäten, den Vergleich der (relativen) Bedeutung der einzelnen Maßnahmen und Schutzwerke, und für die Erstellung von Katastrophenplänen für verschiedene Bruchszzenarien.*

## Keywords

Coast, risk management, flood defence, risk assessment, failure probabilities, vulnerability analyses, Flanders

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## 1. Introduction

The coastal lowlands of the Belgian region Vlaanderen and the Dutch region Zeeuws-Vlaanderen constitute a single cross-border coastal flood unit with a length along the coast-line of 25 km and an landwardth width of 15 km (Fig. 1). If a dike breaches in the Dutch part of this flood unit, the water might well flow into Belgium and vice versa. For historical reasons, both countries have rather different coastal defence approaches and safety standards. These different approaches might result in unbalanced investments for coastal defence schemes in the two sections of the flood unit.

The responsibilities of Dutch and Belgian coastal defence administrations end at the respective national borders. In order to achieve common approaches, a cross-border project, including some form of transnational co-operation with the responsible local authorities like the "Zeeuws-Vlaanderen Water Board", became necessary. Within the INTERREG IIIB project COMRISK (EU-project – [www.comrisk.org](http://www.comrisk.org)) and under the auspices of the North Sea Coastal Management Group, an international platform to implement such a cross-border pilot study is founded. The Coastal Division of the Flemish Community leads the subproject about the Flood Risk in the cross boundary area Vlaanderen-Zeeuws-Vlaanderen. The study is carried out by the consultant IMDC and subcontractors. A steering committee was established to guide and discuss the results. The committee consists of governmental organizations of Belgium (Coastal Division and Flanders Hydraulic Research) and the Netherlands (Rijkswaterstaat, the province and the polder board).

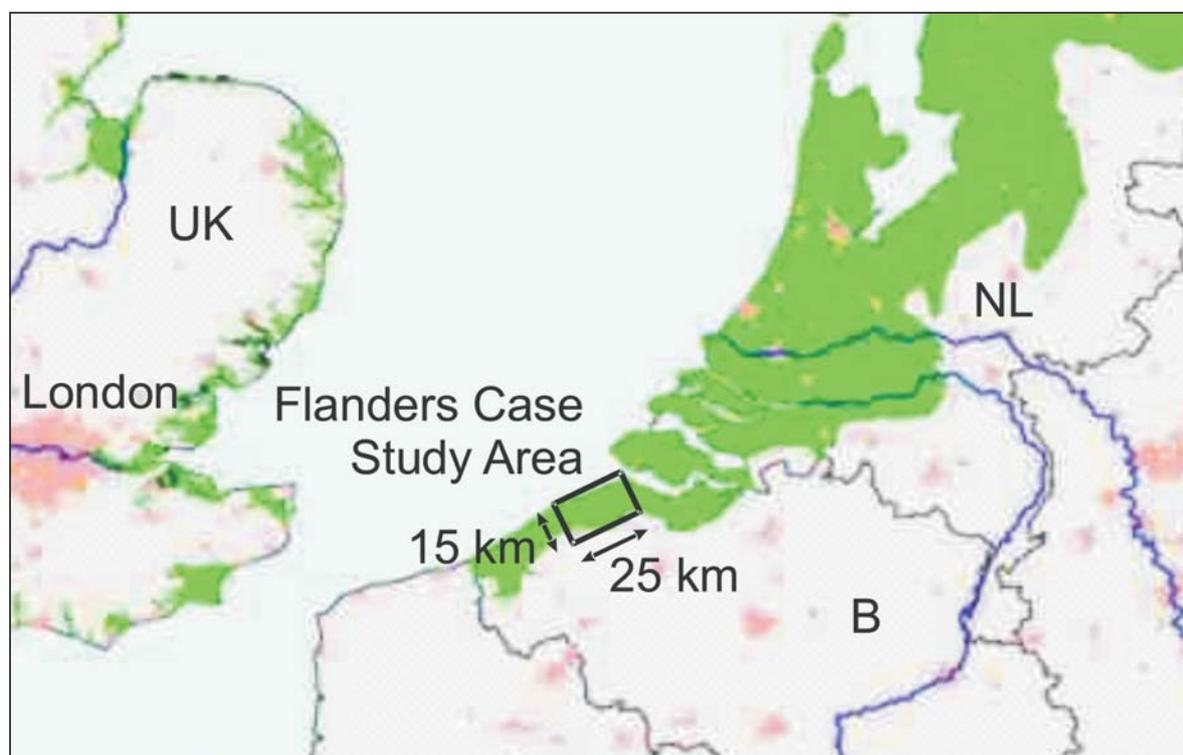


Fig. 1: Coastal flood unit from Zeebrugge in Belgium to Breskens in the Netherlands

## 2. Risk assessment method

Future coastal flooding damage (e.g. in euro) for a certain area and within a specified time horizon, is an extremely stochastic quantity, mostly due to the fact that coastal flooding events are very rare in comparison to the time horizons considered in day to day coastal defence management practice. In this case the return period of a coastal flooding is of the order of magnitude of 1.000 years. Time horizons for specific coastal defence management measures are in the order of magnitude of 10 years (e.g. sand nourishment) to 100 years (e.g. dike construction). The risk for a certain area and within a specified time horizon is defined as the coastal flooding damage that can be expected *on average*, hypothetically considering manyfolds of futures within the specified time horizon that all have a certain probability of occurring. Because of very rare occurrence of coastal flooding events, the risk is approximately linear with the considered time horizon. Therefore it is customary to divide the risk by the time horizon and thus calculating the annual risk (e.g. in euro/year). Another way to explain the annual risk is as the product of the probability of occurrence of an event and the damages (or more general the consequences, comprising economical damages, casualties etcetera), integrated for all possible extreme events. Knowledge of the annual risk can be interesting for a number of reasons: as a basis for comparison between different areas in order to set priorities, to balance insurance premiums with damage compensations, to carry out a cost-benefit analysis to evaluate investments in coastal defence works (e.g. dikes/ beach nourishments), to elaborate contingency plans for possible scenarios of breaching of defences, to compare the relative importance of defences, to inform and sensitize the public about the importance of defences etcetera. But, for coastal defence management purposes one always has to keep in mind that risk and annual risk are only average quantities. One has to be aware when using risk calculation results not to forget the inherent extremely stochastic nature of coastal floodings. In addition to information about the risk, for coastal defence management one has to know about the return period of significant coastal flooding events. This characteristic is left out in the final results of a risk calculation, due to the very definition of risk itself as an average quantity, however intermediate results of a risk calculation can be used to give information about return periods.

The risk assessment method consisted of calculating the expected consequences for a limited number of representative storm events associated with a certain return period. Each of these representative storm events is taken to represent a cluster of possible storms, so that all clusters together represent all possible storm events. Hydrometeorological characteristics are assumed to be comparable for all storm events within the same cluster. The annual risk was calculated as a weighted sum of the probabilities times the consequences for the representative events. Thus the integration over all possible extreme events is discretised as a summation of a limited number of representative events. In this case study 4 representative events were defined, with characteristic return periods 1.000 years, 4.000 years, 10.000 years and 40.000 years. Expected values of the consequences were calculated for each of these. Risk is calculated as a summation for the 4 events of the product of damage and probability. By choosing this risk assessment method we assured that the results of the calculation provided information not only on the risk but also on the return periods of coastal flooding consequences.

### 3. Inventory

#### 3.1 Hydrometeorological boundary conditions

Seventy five years of measurements of water levels and twenty five years of deep water wave measurements at the Belgian coast are available. The return period of extreme storm events resulting in serious flooding is of the order of magnitude of 1.000 years or more, whereas data of hydrometeorological characteristics of storms are limited to a series of less than 100 years. Therefore a very large uncertainty exists on the expected return period of extreme storm events causing serious flooding. For example the standard deviation on the water level of 40 cm for the 1 in 10.000 year storm, corresponds with an order of magnitude of 10 in return period introducing a factor of 10 uncertainty on the calculated annual risk.

The storm surge level of an extreme storm event is the most determining storm characteristic with respect to the associated flooding. Wave characteristics are also important, but found to be relatively well correlated with the storm surge level.

##### 3.1.1 Water level

Water level is the most important parameter and is modeled by summation of surge and tide variations. Fig. 2 shows the variation of the water level, obtained as the sum of the astronomical tide and the storm surge.

The storm duration (and hence the duration of the simulations) was set at 45 hours, following an analysis of historical storms. A spring tide was taken as the water level, with a storm development superimposed. The maximum storm surge is the difference between the water level at the return period concerned and the maximum water level at the selected spring tide. The storm surge varies during the duration of the storm according to a square cosine function, with a surge of 0 m at the beginning and at the end of the storm.

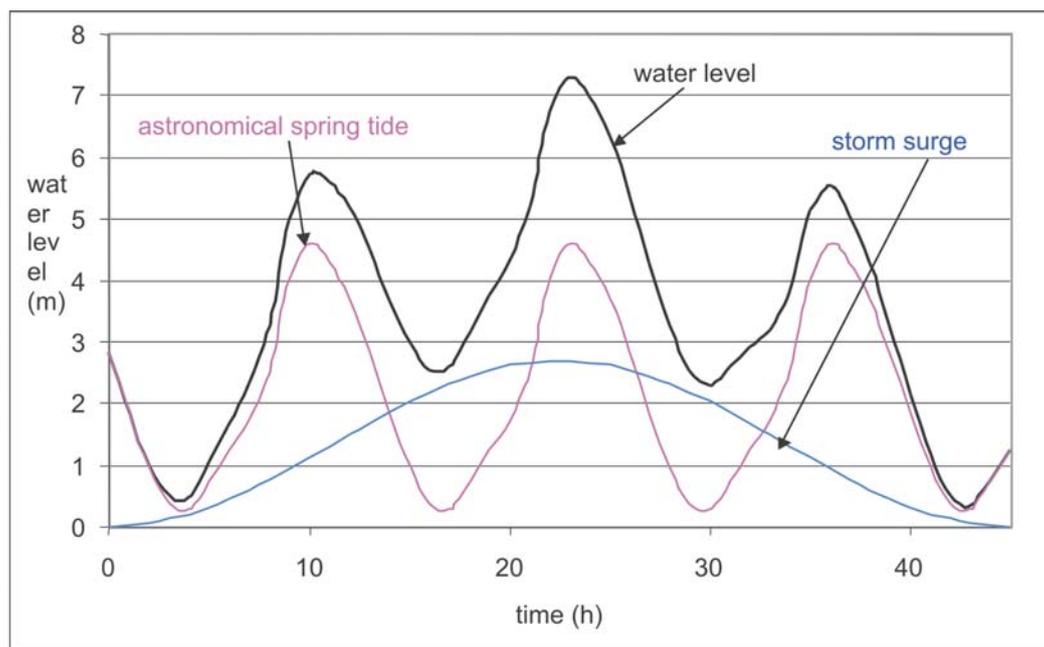


Fig. 2: Model for water level variation during extreme event

### 3.1.2 Waves

Water level dependent statistics on wave heights and periods were established at measurement locations. These wave statistics have been transformed to nearshore wave characteristics using a calibrated numerical wave model (SWAN). The results of this consist of wave parameters at a line along the coast, with a water depth at about -5 m below low water, a position at which the bathymetry will not change considerably during storms.

The wave height variation in time is modeled with a square cosine function with the maximum in accordance with the maximum of the water level but with a period of 125 hours. For the peak period, it is assumed that the steepness of the wave remains constant with respect to the steepness at the storm maximum.

During a storm the beach in front of the dike will erode. Due to the lowering of the bed level, waves will travel more easily towards the toe of the dike, hence to know the wave height at the toe of the dike, it is important to calculate the erosion of the beach.

The erosion of the beach during the storm was determined with DUROSTA (STEETZEL, 1993). This is a time-dependent, one-dimensional model which determines the transformation of the wave height for a given bathymetry using an internal wave model. The most important parameters in the model are the hydrodynamic parameters and the grain diameter. The model takes the effect of hard structures such as sea dikes into account. The transformed waves cause a cross-shore transport of sand and a possible loss of sand at the sea side. After the storm, a new beach profile is obtained. For this profile, the hydrodynamic parameters are determined using the parameters at storm maximum as input. This is slightly conservative, since the profile is further evolved after the peak of the storm.

In principle, the wave height must be determined at the toe of the dike. However, most wave models (Swan, Endec, etc.) produce less reliable wave heights at very shallow water depths. Therefore the wave height at a distance of half a wave length from the toe of the dike is used. However, it is evident that the wave height can never exceed the water depth at the toe of the dike. This is therefore used as a limiting value.

The period to be entered in the overtopping calculations is  $T_m-1.0$ . In DUROSTA the period is assumed to have a constant value. Swan (1D) gives a better prediction of  $T_m-1.0$ . However, for Ostend an underestimate of 11 % was found compared to the measured values. It is not clear to what extent this underestimation is a function of the water depth. It is proposed to use the wave period obtained from Swan, augmented by 20 %, with a minimum of the deep water peak period divided by 1.1 (because the spectrum may be double peaked on shallow water).

Fig. 3 shows an example of the evolution of the beach profile during a storm. Without erosion, the waves are not able to reach the dike, but after erosion, the water depth at the toe is 1.5 m.

## 3.2 Information on the sea defences

Design drawings of the dikes were supplemented with recent beach profiles and dike crest surveys. In addition to existing geotechnical data, soundings and drillings were carried out along the Flemish dikes. Most of the dikes have a complex subsoil structure. The dikes often contain the historical sea defence, which has been breached and repaired on several occasions through time (past millennium). Also water level variations inside the dike are recorded, in order to predict the water level in the dike during an extreme storm.

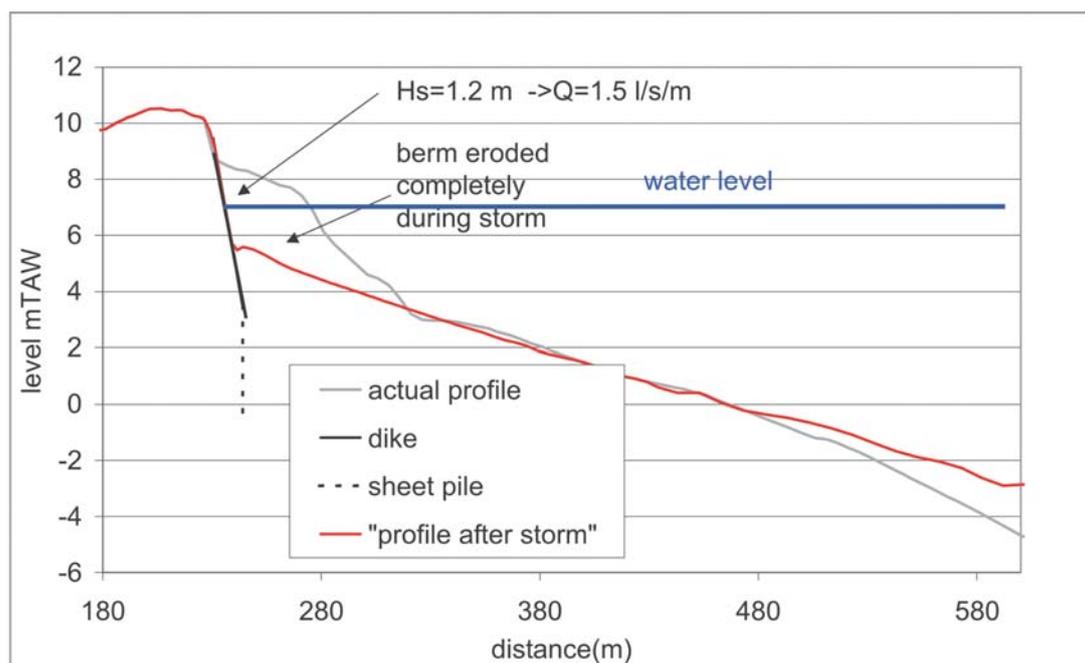


Fig. 3: Example of effect of beach erosion

Various data of beach and dune grain size are available from past measurement campaigns. The topography of the beaches and the dunes was taken from airborne laser altimetry measurements. Possible future changes of this topography (erosion / sedimentation) have not been taken into account.

## 4. Failure mechanisms

### 4.1 Dune breaching

To estimate the erosion risk of the dunes, the Vellinga approach was used (VELLINGA, 1986). An equilibrium profile is fitted to the existing (pre-storm) profile such that the eroded volume in the dune equals the volume deposited in front of the dune (e.g. Fig. 4). The Vellinga profile depends on the water level, the waves and the grain size. A breach is assumed to occur if the dune volume above the maximum water level is smaller than a critical volume.

### 4.2 Dike breaching

Dike breaching results from a cascade of mechanisms. Instabilities of parts of the dikes caused by wave attack and/or overtopping are followed by erosion of the core of these structures until finally breaching.

#### 4.2.1 Wave overtopping

Wave overtopping is calculated using the formula of VAN DER MEER (TAW, 2002). Wave overtopping is of importance if :

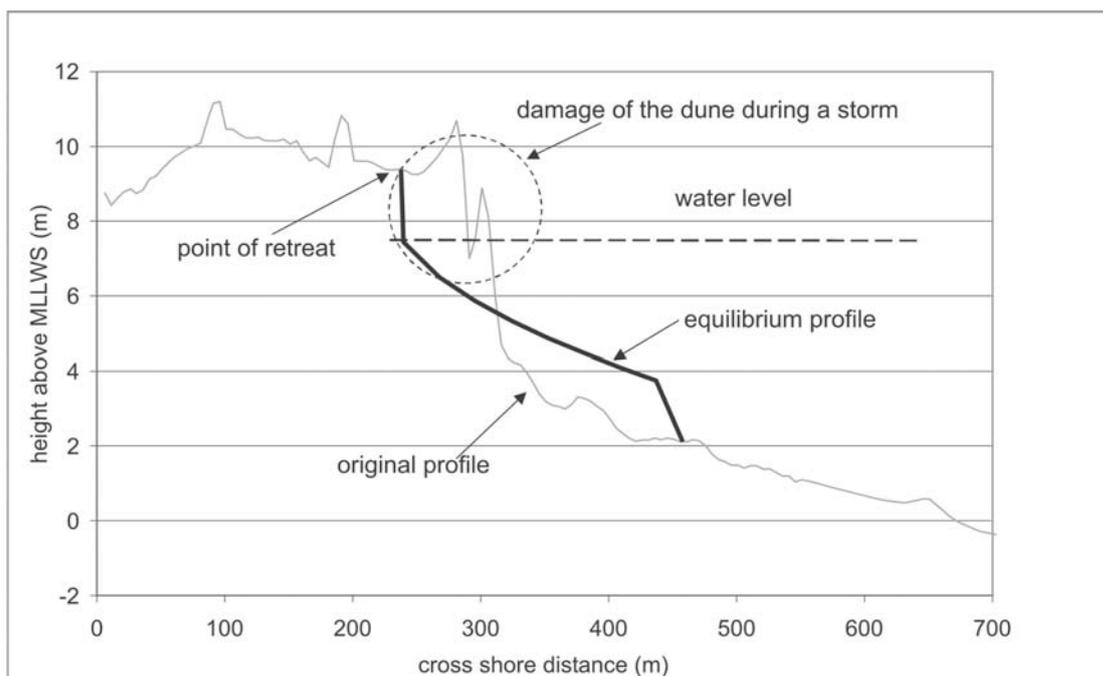


Fig. 4: Dune erosion with indication of original and equilibrium profile

- a) the volume of overtopping water is too large, causing floodings in the inhabited area behind the dike, or
- b) the overtopping rate causes erosion of the crest/inner slope of the dike, eventually resulting in breaching of the dike.

The water velocities over the dike caused by the overtopping are calculated with the formulae of SCHÜTTRUMPF (2003).

#### 4.2.2 Macro stability outer slope

The macro stability of the front slope of the dikes has been tested by means of the SLOPE/W software (Geo-Slope, 2002). The method of Bishop has been used. In general, this method compares the moment of the resistance forces to the moment of the driving forces. The ratio of both moments is the safety coefficient. The resistance forces consist of the shear resistance of the soil, cohesion and the weight of a part of the structure and the soil. The loads consist of the other part of the structure and the soil that result in shear driving moment. To determine the weight of the structure and the soil, the level of the groundwater inside the dike (calculated with GEUZE and ABBOTT, 1961 and verified with groundwater level measurements in the dike) is of uttermost importance. For a large number of predefined slip surfaces, the safety coefficient has been calculated. The smallest value of the safety coefficient, which should be larger than 1, corresponds to the most critical slip surface. The most critical situation occurs at low water after the highest high water.

#### 4.2.3 Revetment

The revetment consists mostly of armed concrete (Belgium) and asphalt or stones (the Netherlands). The stability of the revetment is evaluated with the Dutch safety assessment

methods (TAW, 2004). The armed concrete does not contribute to failure, the asphalt or stones fail, but mostly they are covered with a layer of sand, which does not erode completely during a storm.

#### 4.2.4 Erosion of the core until breaching

To calculate the erosion process during overtopping the sand transport is calculated as the product of a flow rate and an average sand concentration. The assumed average sand concentration is 5 % (based on physical model results). The erosion of the dike body after failure of the outer slope revetment is based on the wave height at the toe of the dike.

#### 4.2.5 Breach growth

Breach growth information was derived from literature data of historical breach formation. A breach grows quite fast in depth (1 to 2 hours). Widthways breach grow data between 0,5 m/hour and 82 m/hour were found. Taking into consideration the extreme hydrometeorological conditions at sea, with waves and wind, a rather large value of 30 m/hour was chosen to be used in this case study as expected value. But it is also found by sensitivity analysis that the effect of this breach growth assumption is large.

### 5. Flood modelling

A two-dimensional hydrodynamic model (Mike21) was used for the flood modelling. The Digital Elevation Models of both Zeeuws-Vlaanderen and Vlaanderen were used for the altimetry. The Zeeuws-Vlaanderen model was available as a 5 m grid, the Vlaanderen model consisted of points with an average density of 3 per 10 m<sup>2</sup>. These DEMs were further improved with land survey data of canal dikes inside the flood plain: these narrow elements are important for controlling the water levels and extend of the inundated area. The final modelling grid is rectangular with a grid size of 25 m. The water level at sea was used as a boundary condition. The roughness is taken uniformly over the entire terrain because sensitivity tests indicated that the roughness values don't significantly influence the extension of the flood area. Stability of the secondary dikes existing in some parts of the coastal plain was assumed. With or without temporary blocking of the flooding propagation by secondary dikes the model results showed that the more distant parts of the coastal plain were not flooded.

### 6. Consequences

To calculate the consequences of flooding, the method developed by Flanders Hydraulics Research is used for Vlaanderen, and the method of Rijkswaterstaat (Directorate General of public works and Water management, the Netherlands) is used for the Netherlands. The two methods are similar. Direct economic damage and human casualties are considered as the consequences of a flooding event. Thus significant consequences are not taken into account, e.g., damage to nature, psychological damage, damage to the economy outside the flooded area.

The methods are based on a GIS-approach. The maximum damage per cell is determined on the basis of land-use maps and information obtained from the National Bureau of Statistics. The damage in the area is then calculated for each category of damage (housing, possessions, agriculture, industry) based on damage functions. Damage functions represent the development of the damage as a function of the depth of inundation, and replacement values or maximum damage values for these categories. This can be done for all potential damage categories. Combining the two sets of data produces the damage per cell. A similar method is used for casualties, with the difference that the maximum rise velocity (Vlaanderen) or the maximum horizontal velocity (the Netherlands) is also used as an input parameter.

## 7. Results and Conclusions

The calculated damages and casualties for the different representative events are shown respectively in Table 1 and Table 2.

Table 1 : Direct economic damage

| Return period | Vlaanderen (B)   | Zeeuw-Vlaanderen (NL) | Total              |
|---------------|------------------|-----------------------|--------------------|
| 1.000 years   | 0                | 5.000.000 euro        | 5.000.000 euro     |
| 4.000 years   | 80.000.000 euro  | 20.000.000 euro       | 100.000.000 euro   |
| 10.000 years  | 400.000.000 euro | 30.000.000 euro       | 430.000.000 euro   |
| 40.000 years  | 700.000.000 euro | 300.000.000 euro      | 1.000.000.000 euro |

Table 2: Casualties

| Return period | Vlaanderen (B) | Zeeuw-Vlaanderen (NL) | Total |
|---------------|----------------|-----------------------|-------|
| 1.000 years   | 0              | 4                     | 4     |
| 4.000 years   | 0              | 6                     | 6     |
| 10.000 years  | 2              | 8                     | 10    |
| 40.000 years  | 4              | 24                    | 28    |

Most damage is in the Flemish part. This is correlated with the relatively high wealth of the coastal community of Knokke-Heist. Most casualties are in the Dutch part. This can be explained by the high rise velocities caused by secondary dikes blocking the flood propagation for a while.

The annual risk was calculated from the numbers in Table 1 resulting in a relatively small value of 100.000 à 200.000 euro/year. However the propagation of the different sources of uncertainties results in an uncertainty with a standard deviation of a factor 10 (order of magnitude) on the annual risk.

It is concluded that, on the one hand, further research is essential to reduce the very large uncertainty on the risk results. Research is most needed on the failure behaviour of the sea defences in the time domain (beach erosion, initiation of damage, breaching, breach growth ...). On the other hand, the risk calculations that are feasible at present, with very limited accuracies, are nevertheless very useful for coastal defence management actions like

informing the public, defining research priorities, comparing the relative importance of measures and defences, and elaborating contingency plans for possible scenarios of breaching of defences.

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