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Reliability Analysis and Breach Modelling of Coastal and Estuarine Flood Defences

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ABSTRACT: Failures of flood defences caused by extreme storm surges can result in severe flooding of the hinterland leading to loss of life and catastrophic damages. In order to quantify the risk of flooding, an integrated risk analysis is being performed within the German 'XtremRisK' project. Within one subproject of XtremRisK, reliability analyses and breach modelling of coastal and estuarine flood defences are performed. In this paper, the methods of the failure probability calculations of coastal and estuarine flood defence structures under the loading of extreme storm surges are discussed. Moreover, the analysis of dike breaches is introduced. Preliminary results of the failure probabilities and the breach modelling are presented exemplarily for estuarine dikes of the Elbe Estuary in the urban area of Hamburg, Germany. Furthermore, gaps in knowledge related to time-dependent failure mechanisms are addressed where an approach is introduced to consider the unsteady conditions of storm surges implemented exemplarily for the failure mechanisms of 'wave overtopping' and 'overflow'. These results are put in context of an integrated risk analysis approach used in XtremRisK.

Keywords: reliability analysis, dike, failure modes, time-dependent analysis, flood risk

1 INTRODUCTION

Impacts of extreme storm surges can cause failures of coastal flood defences and hence flooding of the hinterland resulting in human casualties and enormous economic damages. Especially low-lying coastal areas such as UK, The Netherlands, or Germany are at risk. Due to climate change it may be expected that the risk of flooding will still increase (IPCC, 2007). In order to quantify the present and future flood risk of extreme storm surges, an integrated risk analysis approach is being performed within the German 'XtremRisK' project (www.xtremrisk.de). For this purpose, the source-pathway-receptor model (Figure 1) is applied to an open coast using the example of the island of Sylt, North Sea, and to an estuarine urban area using the example of the Elbe Estuary in Hamburg, Germany. The source-pathway-receptor concept has already been used in flood risk analysis and systematically addresses (Oumeraci, 2004): (i) sources of the risk (storm surge), (ii) risk pathways (way the risk "travels", e.g. across coastal defences or other storm surge protection measures), and (iii) receptors of risk which can be assets such as houses, industry, farming area, etc., or people. The overall approach of XtremRisK comprises four subprojects which deal with risk sources, risk pathways, risk receptors, and their integration as summarized in Figure 1.

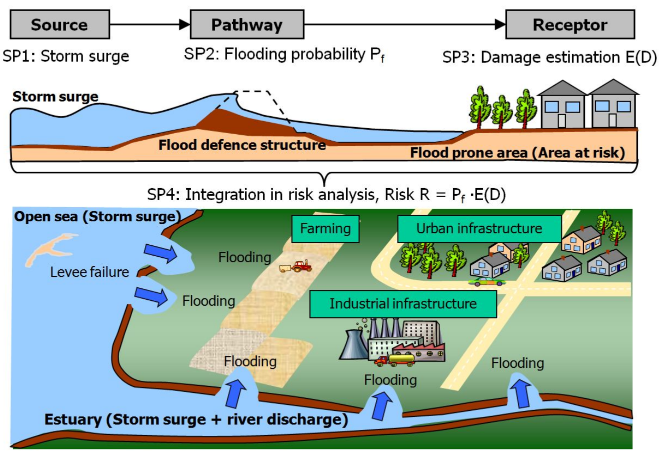

Figure 1. Source-pathway-receptor concept and associated subprojects (SP) in XtremRisK (Oumeraci et al., 2009).

In this project, flood risk is defined as the product of flooding probability Pf and related consequences E(D). Hence, one of the key tasks is to predict the first component of the flood risk, i.e. the failure probability of the flood protection systems which is assumed equivalent to the probability of the hinterland being flooded. Within subproject 2 (SP 2) of XtremRisK, the failure probabilities of flood defences are determined. Moreover, initial flooding conditions at the breach locations (breach width, breach hydrograph, etc.) are modelled. The overall results will be delivered to subproject 3 (SP 3) of XtremRisK for inundation modelling and to subproject 4 (SP 4) for risk integration (Burzel et al., 2010).

This paper presents key elements of the research work of SP 2 aiming at the flooding probability Pf. First, the pilot site of Hamburg is introduced. Second, the applied methods of SP 2, i.e. reliability analysis and breach modelling, are presented. Third, preliminary results of the failure probabilities and the breach modelling using the example of estuarine dikes in Hamburg are presented. Furthermore, gaps in knowledge related to time-dependent failure mechanisms are addressed and an approach is introduced to consider the unsteady conditions of storm surges implemented exemplarily for the failure mechanisms of ‘wave overtopping’ and ‘overflow’. These results are put in context of an integrated risk analysis approach used in XtremRisK. Finally, a summary is given, including a brief description of future prospects.

2 PILOT SITES

The pilot sites, Hamburg and Sylt, are located in the northern part of Germany (Figure 2a). As an example for an open coast, the island of Sylt in the North Sea is analysed whereas the Elbe Estuary of the city of Hamburg serves as an example for an estuarine urban area. Since the focus of this paper is set to exemplarily methods and results of estuarine dikes in Hamburg, only this study area is introduced in the following section.

Hamburg is a mega-city with 1.8 million inhabitants and represents the second largest city of Germany. As a centre for trade, transportation and services, the city is one of the most important industrial sites in Germany with the port of Hamburg being one of the world's leading seaports.

To a large extent, Hamburg’s flood defence structures consist of flood defence walls and dikes with sand core, clay layer and grass cover. Moreover, a variety of structures to close openings of the flood defence line is found such as flood defence gates, tidal gates, flood barriers, etc. The area protected by flood defence structures comprises 270 km², i.e. 1/3 of Hamburg’s territory, where 180,000 people live and 140,000 people work. Within this area goods amounting to a total value of 10 billion Euros are in stock (LSBG, 2007).

The main hydraulic conditions of the pilot sites for Hamburg are a mean high water level of 2.1 mNN (mNN = German datum for water level) and a mean river discharge of 708 m³/s. The highest recorded storm surge water level was measured at 6.45 mNN in 1976 and the highest river discharge at 3,620 m³/s in 1940, respectively. In the past, Hamburg has suffered severe damages caused by extreme storm surges, e.g. the 1962 storm surge led to several dike breaches where more than 300 people lost their lives.

Since a complete risk analysis of the total area of Hamburg would exceed the work capacity in the framework of XtremRisK, typical subareas with characteristic properties were selected. In Hamburg the subareas of Wilhelmsburg, Polder Hamburg Süd, and a part of the city centre were selected for the detailed study (Figure 2b).

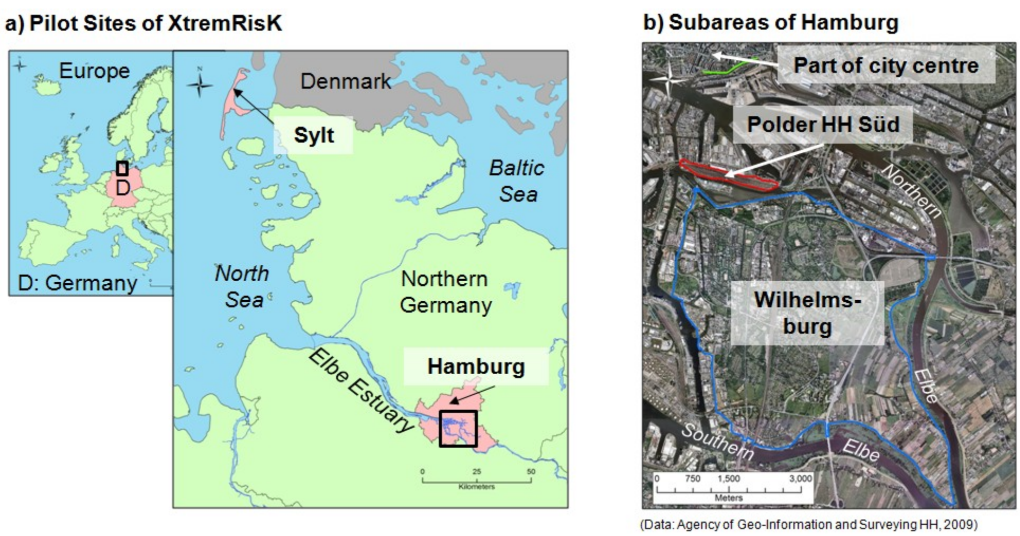

Figure 2. Location of pilot sites selected for this study in XtremRisK: a) Hamburg and Sylt b) Subareas of Hamburg.

3 METHODOLOGY OF SUBPROJECT 2 IN XTREMRISK

Within SP 2 the loading and stability of coastal defences under extreme storm surges were analysed. As input for the analysis, the water levels and wave parameters of an extreme storm surge event together with their occurrence probabilities were provided by SP 1.

As a first step within SP 2, the flood defence line was divided into characteristic sections and the characteristic properties of the flood defences were determined (see section 3.1). On this basis, a reliability analysis was performed in order to calculate the failure probabilities of the coastal flood defences (section 3.2). Moreover, in case of structural failure of sea dikes the breaching of these defences was analysed in order to describe the initial conditions of the flood wave at the breach for an inundation modelling of the hinterland (section 3.3).

The applied methods within SP 2 will be briefly introduced in the following subsections. A more detailed description has been provided by Naulin et al. (2010).

3.1 *Analysis of Flood Defence Line*

Input parameters describing the characteristics of the flood defences were needed in order to perform reliability analysis and breach modelling. For the selected characteristic subareas of the pilot sites, an overview and a detailed parameterisation of all flood defence structures were performed based on an intensive analysis of inventory data such as measurements of the coastal defences as well as geotechnical surveys and digital elevation models. The data collection was carried out in collaboration with the local flood defence authorities of Hamburg.

Using this data basis, which was managed in a geographical information system (GIS), the flood defence line of each subarea was then divided into homogeneous sections with similar characteristics such as type of structure, geometric and geotechnical parameters. Moreover, the hydraulic conditions such as water level and wave conditions were considered for the subdivision. For these sections, all input parameters and their uncertainties were investigated based on the results of the intensive data collection and analysis.

3.2 *Reliability Analysis*

Using a probabilistic approach by taking into account the uncertainties of input parameters and models, a reliability analysis for the flood defences of the subarea Wilhelmsburg was carried out. For this purpose, different failure modes described by limit state equations ($z = R - S$) were analysed (Figure 3a). Since the flood defence line consists of a number of different types of flood defence structures, all failure mechanisms of the documented flood defence structures were examined based on the results of previous projects such as FLOODsite (Allsop et al., 2007) and ProDeich (Kortenhaus, 2003).

For different extreme storm surge scenarios determined by SP 1 the conditional failure probabilities associated to all failure mechanisms were calculated using Monte-Carlo simulations. This procedure of calculating conditional failure probabilities for different extreme storm surge scenarios was chosen since it allowed for performing an event-based inundation modelling and damage estimation.

For each type of flood defence structure, failure mechanisms were organised in a fault tree. The structure of the fault tree represents the different chains of events leading to an overall failure of the flood defence structure (top event) which was defined in this study as flooding of the hinterland.

An overview of a general structure of a fault tree combing different limit state equations for dikes is presented in Figure 3b. From the failure probability of each flood defence section, the overall failure probability of the flood defence system of each subarea was calculated also using a fault tree approach.

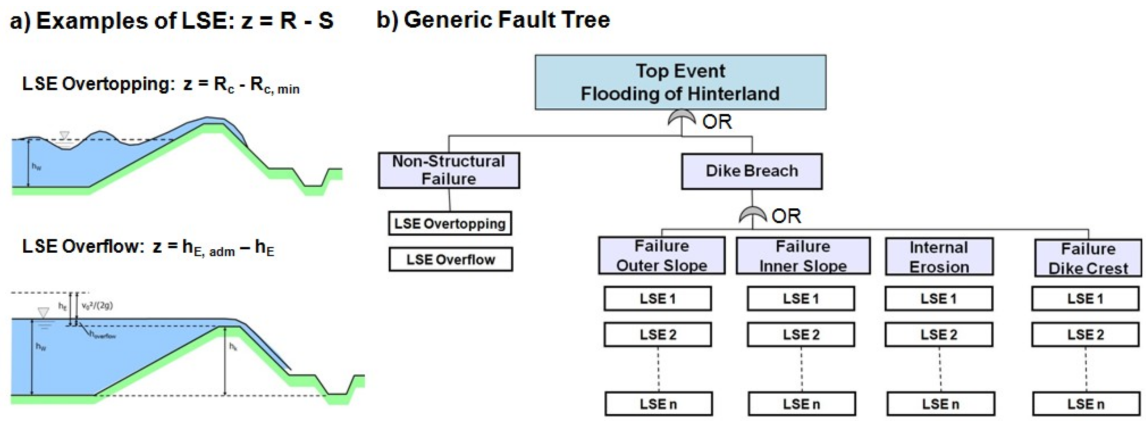

Figure 3. Limit state equations (LSE) of dikes: a) examples of LSE overtopping and overflow b) generic fault tree.

Reviewing failure mechanisms and fault trees of different flood defences based on a literature study, knowledge gaps were identified and an attempt was made to close them by including new or updated limit state equations and by developing missing fault trees for structures not yet considered, e.g. updating limit state equation for critical velocity of grass slopes of dikes according to an approach described by Tuan and Oumeraci (2010b), and including limit state equations for cross-shore profile response of dunes due to wave impact and overwash by applying analytical models developed by Larson et al. (2009).

For the failure probability calculations software tools such as the FLOODsite software tool RELIABLE (Van Gelder et al., 2008) or ProDeich (Kortenhaus, 2003) were applied. For this purpose, all relevant failure mechanisms and fault trees were implemented within the software tools.

The results of the probability of flooding were delivered to SP 4 for risk integration. Moreover, the fault tree analysis allowed determining the probability of breaching of dunes and dikes and gave an indication of the causes of breach initiation, e.g. wave impact on outer slope or overtopping on inner slope. Preliminary results of the failure probability calculations are presented in the next section. However, first the methodology of the breach modelling is introduced in the following subsection.

3.3 *Breach Modelling*

The total failure of the flood defences includes breaching of flood defence structures such as sea dikes. The results of the reliability analysis indicated if and where breaching might occur, i.e. sections with a high probability of breaching. Moreover, the identification of causes and failure modes that may induce an initial breach can be assessed by a fault tree analysis. In case of a high probability of breaching, the process was further analysed and modelled in order to specify the initial conditions of the flood wave for the inundation modelling of the hinterland.

The causes of breach initiation depend on the structure of the dike and on the hydraulic and morphological boundary conditions. In general, several causes for the initiation and formation of a breach can be distinguished, e.g. wave overtopping, overflow, wave impact and seepage. Breaching of sea and estuarine dikes are caused by the following main failure mechanisms (TAW, 1999): (i) erosion and sliding initiated on landside slope by wave overtopping and overflow, and (ii) erosion of seaward slope resulting from breaking wave impacts and the flow induced by wave run-up and run-down. While breaking wave impacts on the seaside slope act on a very limited area and during very short, intermittent periods, the shear stress related to wave overtopping acts on the entire landside slope and during longer time periods.

There are different breaching models for the different causes of breach initiation available, e.g. breaching initiated on the landside by wave overtopping and overflow is described by D'Eliso et al. (2006) and Tuan and Oumeraci (2010a,b) as well as breaching initiated on the seaside by breaking wave impacts is described by Stanczak et al. (2008). Depending on the loading conditions (wave overtopping/ overflow or breaking wave impacts) and thus depending on the breach initiation (landside or seaside) one of the above introduced breaching models was applied to the case study area.

As a result, the breach development could be described in time with specifications on breach initiation, breach duration, and the final breach width and depth. Furthermore, the outflow hydrograph of the breach could be estimated. The results of the initial condition of the flood wave were delivered to SP 3 where inundation modelling of the hinterland and damage estimation was performed.

4 PRELIMINARY RESULTS OF ESTUARINE DIKES IN HAMBURG

Preliminary results are exemplarily given for estuarine dikes of the subarea of Hamburg Wilhelmsburg (Figure 2b) analysing the first XtremRisK scenario of an extreme storm surge event in Hamburg under current climate conditions. In the following section, the hydraulic conditions of the extreme storm surge as well as the intermediate results of the analysis of the flood defence line, the reliability analysis, and the breach modelling are described.

4.1 *Hydraulic Condition of Extreme Storm Surge Scenario*

In SP 1, different extreme storm surge scenarios under current and future climate change conditions are determined. The first investigated storm surge event under current climate conditions has a peak water level of 8.0 mNN at the gauge Hamburg St. Pauli which is 5.9 m above the mean high tide level and 0.7 m above the design water level. The occurrence probability was determined to $1.0\cdot10^{-5}$ per year based on multivariate statistics (Wahl et al., 2010). The results of the wave modelling simulated wave heights H_S up to 0.8 m with peak periods of up to $Tp = 6.0$ s. For the reliability analysis, the duration of the peak water level was estimated to 7.0 hours considering the time of exceedance of a threshold water level of 5.6 mNN which is 3.5 m above mean high water level, i.e. equivalent to the definition of a ‘very extreme storm surge’ according to the The Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency). Hence, preliminary results of failure probabilities represent an overestimation of what might actually occur. However, for the breach modelling the unsteady conditions in terms of the time series of the water level were considered.

4.2 *Analysis of Flood Defence Line*

The main part of the flood defence line of Hamburg Wilhelmsburg, i.e. 19 km out of 23 km, consists of dikes. The dikes are built of a sand core, a clay layer with a thickness of up to 2.0 m and a grass cover on top. The crown heights of the dikes vary from 7.80 mNN to 8.35 mNN and in general the outer and inner slopes are 1 in 3.

The result of the division of Wilhelmsburg’s flood defence line into “homogeneous” sections according to similar characteristics such as type of structure, geometric and geotechnical parameters as well as hydraulic conditions is shown in Figure 4. Overall the flood defence line is divided into 84 sections. Out of these sections a total number of 62 segments are dikes and 7 sections are walls. Furthermore, there are 15 so called “point structures” such as gates etc.

Based on an intensive data analysis, the 62 dike sections are parameterised and over 80 input parameters are determined. In case of a lack of data – especially in the case of geotechnical parameters – the data and their uncertainties were estimated by literature references.

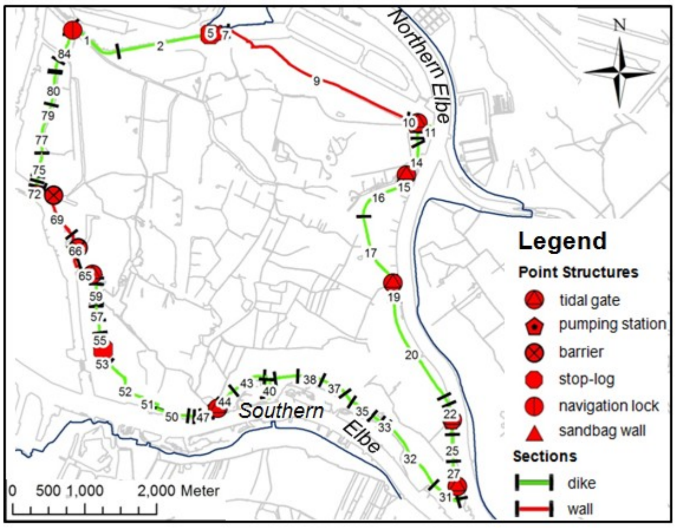

Figure 4. Sections of the flood defence line of the study subarea Wilhelmsburg, Hamburg.

4.3 *Failure Probabilities*

For the reliability analysis of dikes a total of 22 failure mechanisms are considered in this study. An overview of the applied limit state equations is given in Table 2. Two failure modes leading to non-structural failure, i.e. overflow and wave overtopping, as well as 20 failure mechanisms inducing dike breaching are analysed. For further details it is referred to Kortenhaus (2003) and Allsop et al. (2007).

Considering the uncertainties of input and model parameters, the conditional failure probabilities of the failure mechanisms for each of the 62 dike sections under the loading of the first extreme storm surge scenario were calculated by using Monte-Carlo-Simulations. The combination of all failure modes leading to the top event of inundation is performed by a fault tree approach whereas the general structure of the fault tree shown in Figure 3b is applied.

The overall results of the failure probabilities of the top event, i.e. flooding of the hinterland, reach very high values of almost Pf = 1.0 per year for 45 out of 62 dike sections of the flood defence line. The dominating failure mechanisms leading to the high probability of flooding are identified as non-structural failure in terms of wave overtopping and overflow due to the very high storm surge level as compared to the dike heights. In order to analyse the structural stability of the inner slope, the results of the failure probabilities of the failure of the inner dike slope are examined. For most dikes the failure probabilities of the failure of the inner dike slope are rather low ($1.0 \cdot 10^{-4}$ per year). Only in some areas higher values (between 1.0·10-2 and 1.0·10-3 per year) are calculated. These dike sections are identified as weak spots since they have less resistant inner slopes or are exposed to more severe hydraulic loading. Breach modelling will be applied to these "weaker" sections as described in the next subsection.

However, failures of dikes represent highly complex hydrodynamic and morphodynamic processes. The applied reliability analysis uses relatively simple limit state equations combined within a fault tree analysis. Although the approach represents an adequate tool in order to analyse the performance of the flood-defence system and its components, and in order to identify weaker areas with a higher probability of flooding, there are still gaps in knowledge like e.g. time dependent processes.

Table 1. Limit state equations (LSE) of failure mechanisms of dikes applied in this study with details on name, comparative parameters of LSE, units of LSE, and time dependence as function of storm surge parameters.

LSE No.	Name	Comparison of...	Unit	Time-Dependence as Function of Storm Surge* t_S	h_W	H_S
Non-Structural Failure						
1	overflow (functional failure)	overflow rates (or energy heights)	m³/s/m or m/m		X	
2	wave overtopping (functional failure)	overtopping rates (or freeboards)	m³/s/m or m/m		X	X
Failure of Outer Slope						
3	velocity wave run-up	wave velocities	m/s	X		X
4	wave driven erosion	times	h	X	X	X
5	wave impact	cohesions	kPa			X
6	cliff erosion by wave impact	times	h	X	X	X
7	erosion of revetment armour (rock)	stone diameters	m			X
8	uplift of the revetment	forces of revetment elements	kN/m			X
9	deep slip (Bishop)	moments of single Bishop's slices	kNm			
Failure of Inner Slope						
10	overflow velocity	overflow velocities	m/s	X		X
11	wave overtopping velocity	wave overtopping velocities	m/s	X		X
12	erosion by overflow/ wave overtopping	times	h	X	X	X
13	sliding of clay layer**	times & forces	h & kN	X	X	X
14	clay uplift**	times & forces	h & kN	X	X	X
15	deep slip (Bishop)	moments of single Bishop's slices	kNm			
16	partial breach	times	h	X	X	X
Sliding and Internal Erosion						
17	sliding of dike with clay cover (functional failure)	forces	kN/m²		X	
18	piping**	times & pressure gradient	h & -	X	X	X
19	matrix erosion**	times & sediment diameter	h & mm	X	X	X
Failure of Dike Top						
20	erosion of inner slope & dike top failure**	times & moments of single Bishop's slices (sand)	h & kNm	X	X	X
21	sliding of inner slope & dike top failure**	times & forces & moments of single Bishop's slices (sand)	h & kN & KNm	X	X	X
22	clay uplift of inner slope & dike top failure**	times & forces & moments of single Bishop's slices (sand)	h & kN & KNm	X	X	X

* t_S = time of storm surge duration [h], h_W = water level [mNN], H_S = significant wave height [m]
** Combination of different LSE

In the following, the aspect of time-dependent processes as a function of the storm surge parameters is further discussed. Table 1 shows the dependencies of the failure mechanisms on storm surge parameters such as duration time, water level, and wave parameters. However, until now only single constant values of each parameter have been considered. In order to show the significance of the consideration of the unsteady state of the storm surge event, the failure mechanisms of overflow and wave overtopping are adopted and analysed in more detail.

For this purpose, at first the deterministic combined overtopping and overflow discharges are determined using two different ways to account for the storm surge parameters: (i) constant maximum water level and constant associated wave parameters with a storm surge duration of 7 h as applied in the reliability analysis (see section 4.1), (ii) unsteady conditions of water level and wave parameters using a time series of ca. 28 hours with time steps of 15 minutes.

The combined overtopping and overflow discharges are calculated according to an approach after Bleck et al. (2000) using existing weir formulae and wave overtopping formulae for all 84 sections of the flood defence line considering 62 dike sections as sloped structures and 22 sections as vertical structures.

The results of taking into account the unsteady conditions of water level and wave parameters show that within a time period of 2.5 hours water overtops and/or overflows the dikes and maximum values of mean discharges of up to 0.660 $m^3/s/m$ are determined. Considering the lengths of the flood defence sections and the time of the storm surge, the total overtopping volume of all 84 sections amounts to 10.5 million m^3.

In contrast using the mean overtopping discharge under consideration of constant maximum water level and wave parameters over storm surge duration of 7 hours, the overtopping volume is estimated to 74.5 million m^3. The time-dependent calculation of volumes instead of discharges with constant parameters over a storm surge event has considerable advantages since it represents a better approximation of the time-dependent process, i.e. no overestimation of overtopping volume. Furthermore, the storage capacity of the hinterland is taken into account, i.e. exceedance of critical overtopping discharge might occur for a short period at the peak of the storm surge; however this does not necessarily lead to flooding.

As a next step, it is intended to convert the present deterministic approach of comparing admissible overtopping volumes with actual overtopping volumes to a probabilistic procedure. Moreover, the realisation of taking into account the unsteady condition of storm surge level is further analysed and adopted for other main failure mechanisms.

4.4 *Breach Modelling*

The results of the reliability analysis illustrated that overflow and wave overtopping represent the major forcing of the first analysed storm surge scenario in Hamburg Wilhelmsburg. For this reason wave overtopping-induced erosion of the inner slope of grassed sea-dikes is simulated. The breach initiation is modelled using the BREID model which is a numerical model for simulating BREaching of Inhomogeneous sea Dikes (BREID) developed by Tuan and Oumeraci (2010a,b). The modelling of breach initiation is based on the approach of excess bed shear for grass erosion. For the determination of the bed shear stress, the flow structure of wave overtopping on the inner slope is refined according to turbulent wall jet formulations in order to account for the high turbulence with entrained air bubbles for the conditions of wave overtopping on grass slopes. The critical velocity for grass erosion is determined based on depth-dependent strength concept together with a mobilized shear strength coefficient (Tuan and Oumeraci, 2010b). The results of the modelling of breach initiation - which are described in detail in Naulin et al. (2010) - revealed that for moderate grass conditions, the erosion of the grass layer was initiated to a depth of only 7.0 cm; i.e. a breach would not develop.

Further studies will analyse the effects of different grass conditions. Therefore, the results of laboratory experiences analysing the root volume ratio of grass samples in Hamburg Wilhelmsburg will be implemented in the model. Moreover, the existence of possible weak spots in the grass layer such as holes or cracks will be analysed. In case of a breach initiation, the breach development will be further analysed. Finally, the breach width and the breach outflow hydrograph will be obtained in order to specify the initial conditions of the flood wave at the breach for inundation modelling of the hinterland.

However, regardless of whether a full breach would develop, the analysed extreme storm surge leads to a total overtopping volume of 10.5 million m^3 and therefore to severe flooding of the hinterland. A detailed analysis of the inundation modelling and damage estimation of the hinterland will be carried out by SP 3 using the time series of the discharges of the flood defence sections as input parameters.

5 SUMMARY AND FUTURE PROSPECTS

The German research project XtremRisK (www.xtremrsik.de) performs an integrated flood risk analysis for extreme storm surges and consists of four subprojects. The city of Hamburg serves as a pilot site for an estuarine urban area, and the island of Sylt as an open coast. Subproject 2 (SP 2) of XtremRisK deals with a probabilistic reliability analysis and breach modelling of coastal and estuarine flood defences.

In this paper, the methods to determine failure probabilities of flood defence structures as well as the methods for breach modelling of sea dikes are outlined. Furthermore, preliminary results of failure probability calculations and breach modelling are given exemplarily for estuarine dikes in Hamburg with crest heights between 7.80 mNN and 8.35 mNN and for a first extreme storm surge scenario with water levels up to 8.2 mNN and duration of 28 h (7 h above 5.6 mNN), modification of wave height and period up to 0.8 m and 6.0 s, and a probability of occurrence of $1.0 \cdot 10^{-5}$ per year. The reliability analysis allowed identifying relevant failure mechanisms and "weaker" dike sections for the case investigated here leading to 45 dike sections which will either overflow or overtop (failure probability of $P_f \sim 1.0$). The total overtopping volume for all 84 flood defence sections was determined to 10.5 million m³. Hence, the analysed extreme storm surge directly leads to severe flooding. Since wave overtopping and overflow were identified as the major forcing in this scenario, a breach model simulating overtopping and grass erosion on the inner dike slope was applied. As the results showed, the erosion of the grass layer was initiated to a depth of only 7.0 cm; i.e. a breach would not develop for moderate grass conditions. Further studies will analyse the effects of different grass conditions and possible weak spots in the grass layer such as holes or cracks. The overall results of flooding probabilities and initial flooding conditions will be delivered to subproject 3 in order to model the inundation of the hinterland for damage estimation and to subproject 4 in order to combine the results in an integrated risk analysis.

Future prospects within subproject 2 include further applications of the introduced methods of reliability analysis and of breach modelling for both pilot sites. Moreover, it is intended to update and further develop limit state equations and fault trees. For example, methods are analysed in order to consider the time dependence of failure mechanisms in terms of the unsteady conditions of the storm surge, e.g. by changing the limit state equations for 'wave overtopping' and 'overflow' from discharges to volumes as introduced in this paper. Furthermore, missing limit state equations and fault trees for failure mechanisms and structures not yet considered should be included in the reliability analysis, e.g. updating limit state equation for critical velocity of grass slopes of dikes according to an approach described by Tuan and Oumeraci (2010b), and including limit state equations for overwash of coastal dunes using analytical models developed by Larson et al. (2009).

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