Failure Mechanisms of Flood Defence Structures

Status Report Of Activity 2.2 & 2.3

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May 2010 (Updated: December 2012)

Summary:
This report describes the failure mechanisms of flood defence structures. At first a general introduction of the methods of the reliability analysis of flood defences including failure mechanisms and fault tree analysis is given. Afterwards the main failure mechanisms and associated limit state equations (LSE) of linear flood defence structures such as dikes, flood defence walls and coastal dunes are described. Therefore, in appendices A to C a catalogue of LSE is given where each LSE is illustrated by a brief description, a definition sketch, one or more possibilities of LSE, a description of the variables of the resistance and the loading variables and the associated reference. Furthermore, in appendices D to F a catalogue of fault trees is given. For each flood defence structure the fault tree combining different LSE to the TOP-event “flooding” is shown.

Das diesem Bericht zugrunde liegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung und Forschung unter dem Förderkennzeichen 03F0483A gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt beim Autor.
ABSTRACT

Within XtremRisK subproject (SP) 2 one task is to determine the loading and the stability of all components of flood defence systems. Therefore, a reliability analysis of coastal flood defences is performed, i.e. the determination of the failure probability (and thus the flooding probability) which is the first component of flood risk (defined as the product of probability $P_f$ and related consequences $E$ here).

In this report the basic concept of the reliability analysis of flood defences is summarised. Furthermore, an overview of failure mechanisms and associated limit state equations of flood defences such as sea dikes, flood defence walls and coastal dunes are given in a catalogue style.

In appendices A to C a catalogue of limit state equations (LSE) is given where each LSE is illustrated by a brief description, a definition sketch, one or more possibilities of LSE, a description of the variables of the resistance and the loading variables and the associated reference.

Furthermore, in appendices D to F a catalogue of fault trees is given. For each flood defence structure the fault tree combining different limit state equations to the TOP-event “flooding” is shown.
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1 Introduction

1.1 Background and Motivation

In the past, storm surges have led to major damages, also along the German coastline. Due to climate change it may be expected that the risk of flooding will increase in the coming decades. In order to enhance the knowledge related to extreme storm surges and the assessment of the associated risk, the joint research project XtremRisK was initiated. The general aim of the project is to develop methods to quantify the overall flood risk under present and future climate change conditions for an open coast (Island of Sylt, North Sea) and an estuarine urban area (Hamburg, Germany) using an integrated risk analysis approach (Oumeraci (2004)).

In this respect, one of the major tasks within XtremRisK subproject (SP) 2 is to determine the loading and the stability of all components of flood defence systems. Therefore, a reliability analysis of coastal flood defences is performed, i.e. the determination of the failure probability (and thus the flooding probability) which is the first component of flood risk (defined as the product of probability \( P_f \) and related consequences \( E \) here). Moreover, the total failure of the defence components includes the breach and breach development of flood defence structures such as sea dikes and natural barriers such as dunes. These tasks in terms of a reliability analysis and the modelling of the breaching of coastal flood defences within SP 2 are summarised in a flow chart (see Fig. 1.1). A short description is given in the following paragraph.

![Flow chart of the tasks within XtremRisK-subproject (SP) 2](image)

As shown in the flow chart (Fig. 1.1), as input parameters in SP 2 the extreme storm surge scenarios developed in SP 1 are applied. Moreover, as input a description of the flood defence...
structures was performed in SP 2. Therefore, characteristic subareas of pilot sites for the island of Sylt and the Elbe estuarine area of the megacity Hamburg were selected. For these subareas, an overview and a detailed description of all flood defence structures were given. The flood defence line was divided in sections with similar characteristics such as type of structure, geometric and geotechnical parameters (see XtremRisK progress report SP 2.1; Naulin et al. (2009)).

For the reliability analysis, the limit state equations \( Z (Z = R - S) \) comparing strength (R) and loading (S) for all failure mechanisms of the documented flood defence structures are examined based on the results of previous projects such as FLOODsite (Allsop et al. (2006)) and ProDeich (Kortenhaus (2003)).

Using a probabilistic approach considering the uncertainties of the input parameters and models, the failure probability is first calculated for each section of the entire defence line using a fault tree analysis combining all failure modes. From this, the overall failure probability for the flood defence system for each subarea is calculated. The results of this reliability analysis will be given to SP 4 in order to perform a full risk analysis.

The modelling of breaching is carried out for the flood defence structures such as sea dikes and natural barriers such as coastal dunes. As a result, the breach development can be described in time with specifications on breach initiation, breach duration, and the final breach width and depth. The results (outflow hydrograph and water depth at the breach) are to be used in SP 3 and SP 4 as input parameters for the simulation of the flood wave propagation and inundation and the related damages in the study areas.

### 1.2 Objectives

The objectives of this report are to summarize and examine the existing limit state equations for all failure mechanisms of the documented flood defence structures based on a literature review.

Therefore, at first in chapter 2 of this report a short introduction on the general concept of the reliability analysis is given.

Afterwards, the limit state equations for all failure mechanisms of the main linear flood defence structures such as sea dikes, flood defence walls and coastal dunes are summarised. The failure modes and limit state equations in this report are given in a catalogue style as follows:

- **dikes** (predominantly with a sand core, clay cover and grass layer) (see appendix A)
- **flood defence walls** (see appendix B)
- **coastal dunes** (see appendix C)

The existing limit state equations are examined based on the results of previous projects such as PROVERBS (Oumeraci et al. (2001)), ProDeich (Kortenhaus (2003)), and FLOODsite (Allsop et al. (2006)). Allsop et al. (2006) provide a definitive listing of reliability equations for failure mechanisms of generic flood defence structures or assets. Over 80 different limit
state equations were sorted within a matrix classified by generic flood defence type and loading categories. A listing of the limit state equation was performed in form of a catalogue template.

The focus of this report is to give a short but more detailed description and to put the limit state equations into a context. Since some of the failure mechanisms do not lead to a full structural or functional failure and therefore are initiating events, a context with other limit state equations is needed. One example of an initiating failure mechanism is for example the critical velocity on the outer slope of a dike due to wave action. If the critical velocity is exceeded the erosion of the outer slope begins but the dike does not fail due to a full structural failure such as breaching. The description of the links between the different failure modes is needed for the fault tree analysis where all limit state equations are combined leading to the TOP-event, i.e. flooding of the hinterland.

Moreover, some existing limit state equations for dikes were adjusted, e.g. merged in one main limit state equation, on the basis of failure scenarios developed by Kortenhaus (2003) who set up a probabilistic design concept for sea dikes.

Furthermore, this report is restricted to relevant failure mechanisms for coastal and estuarine flood defence structures that are exposed to the loads of extreme storm surges. Extreme storm surges are characterised by extreme high water levels and extreme wave conditions. The occurrence probability is low and the time of storm duration is with six hours for the maximum value of the storm surge level (or with a maximum of up to 36 hours by considering three tides) rather short in contrast to fluvial structures where high water can last until a period of up to a few days.
2 Reliability Analysis of Flood Defences

In the following chapter theoretical background of reliability analysis of dikes are given. To implement/analyse possible failures in a reliability analysis failure mechanisms need to be described and the corresponding limit state equations (section 2.1) including input parameters (section 2.2) and uncertainties (section 2.3). Next failure probability calculations (section 2.4) and their combination in a fault tree analysis (section 2.5) are described.

2.1 Failure Mechanisms and Limit State Equations

In order to implement and analyse failures mechanisms of flood defences in a reliability analysis they need to be described by corresponding limit state equations (LSE). The LSE compares the load applied to the structure and the strength thereof by the following general equation:

\[ z = R - S \]  \hspace{1cm} (0.1)

with:

- \( R \) = resistance/ strength \((French: \ résistance)\)
- \( S \) = load \((French: \ sollicitation)\)

Parameter \( R \) represents the resistance/strength of the structure and is described as a function of geometrical and/or geotechnical properties of the structure, such as dike crown height, thickness of the revetment layer, cohesion of the soil, etc..

Parameter \( S \) represents the load applied to the structure and is described as a function of hydraulic conditions, such as water depth, wave parameters, etc..

Failure occurs when loading exceeds strength of the structure, i.e. \( S > R \), and the structure functions when \( S \leq R \). Therefore, \( z = 0 \) describes the limit state, i.e. the boundary between functioning and failure.

In appendices A to C a catalogue of limit state equations (LSE) is given where each LSE is illustrated by a brief description, a definition sketch, one or more possibilities of LSE, a description of the variables of the resistance and the loading variables and the associated reference.

2.2 Input Parameters of Limit State Equations

The input parameters of the limit state equations of failure mechanisms can be distinguished according to their properties in hydrodynamic (section 2.2.1), geotechnical (section 2.2.2) and geometrical parameters (section 2.2.3) as described in the following using the example of dikes.
2.2.1 Hydrodynamic Input Parameters

As hydrodynamic input parameters of limit state equations the water level and wave parameters in front of the dike toe as well as the velocities and layer thicknesses on the seaward and landward slope as well as at the dike crown are considered.

For the determination of the hydrodynamic input parameters at the toe of the structure, different factors such as the prevailing wind, the water level in deep water, the prevailing sea conditions and the bathymetry or topography of the flood plain are of importance. Since water level and wave data are generally only available in the far field of the structure, transformation of waves in the near field of the structure or to the toe of the structure has to be performed. This transformation is highly dependent on the local topographical conditions and therefore cannot be generalized. The determination of hydrodynamic input parameters, including the necessary distribution functions for the uncertainty, can in principle be performed in three steps: from the far field (deep water) to the near field (shallow water) to the structure as shown in Fig. 2.1.

![Diagram](image)

**Fig. 2.1:** Determination of water and wave parameters at the structure including distribution function (Kortenhaus (2003))

2.2.2 Geotechnical Input Parameters

For the applied failure mechanisms of a dike, it is necessary to determine or estimate approximately 50 geotechnical input parameters describing the soil properties (such as internal
friction angle $\phi$, undrained cohesion $c_u$, clay density $\gamma_k$, sand density $\gamma_s$, thickness of clay layer of slopes and crown, etc.) including their distribution functions.

In general the determination of soil parameters requires three steps, each containing a number of uncertainties (De Groot (2001)):

- measurement (random samples in the field or in the laboratory, for example, the point resistance of pressure gauge $q_c$),
- transfer of measured parameters to relevant parameters of the analysis (e.g. calculation of undrained cohesion $c_u$ from the point resistance $q_c$),
- interpolation or extrapolation of measured parameters to the point where the analysis should be performed (e.g. along the dike at the location with worse soil conditions).

More general information on geotechnical input parameters is missing since the parameters may vary strongly depending on the location. Therefore, most input parameters have to be estimated or are based on experts’ knowledge. It is worth mentioning that this problem occurs also in deterministic analyses. In this case the error could result in even more significant consequences due to the unrecognized uncertainties.

### 2.2.3 Geometric Input Parameters

The geometric input parameters describe the cross-section of the dike, e.g. with specifications on the angle of the outer slope and the landward slope, height and width of the dike, and a possible existing berm. As an example of a typical estuary dike, a standard cross section of a dike as well as the simplified parameterisation of the geometric input parameters are shown in Fig. 2.2.
2.3 Uncertainties

In reliability analysis uncertainties are introduced since the parameters are not used deterministic (exactly known) but are unknown instead, hence uncertain. Uncertainty of the considered input parameters and models in reliability analysis generally result from the following sources (Fig. 2.3; Kortenhaus (2003)):

- "Fundamental" or statistical uncertainties: natural, inherent uncertainties that are due to random processes in nature and cannot be reduced (always included in measurements);
- Data uncertainty: measurement error, heterogeneity of data, errors during data processing, non-representative representation of the measurement due to inadequate temporal and spatial resolution;
- Model uncertainty: insufficient representation of the physical processes in nature;
- "Human error": any errors during manufacture, deterioration, maintenance, as well as other human errors that are not covered by the model. They are often not considered in
In certain circumstances these uncertainties and errors can lead to failure of a structure whereat a (deterministic) calculation by taking into account the mean values only would not indicate a failure of the structure. Therefore, for a probabilistic risk analysis or reliability analysis the uncertainties have to be explicitly known or estimated.

In order to describe uncertainty usually mean values and standard deviations are used, to a lesser extent coefficients of variation are applied. The mean value of measured data is defined as follows:

$$ \mu_x = \frac{1}{N} \sum_{i=1}^{N} x_i $$  \hfill (0.2)

Where the parameter $\mu_x$ is the mean of the data, $N$ is the number and $x_i$ are the single values of the available data.

The standard deviation $\sigma_x$ is defined as follows:

$$ \sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu_x)^2} $$  \hfill (0.3)

The coefficient of variation $\sigma^*$ results from the ratio of standard deviation and mean value of the data as follows:
The coefficient of variation expresses how often a standard deviation is included in the mean value and represents an appropriate method as a relative value for comparison of the uncertainties of different parameters. In probabilistic analyses the specification of the coefficient of variation alone is not sufficient, since for the necessary assumption of a distribution function both the mean and the standard deviation must always be known.

Information on the uncertainties of the input parameters and models within a probabilistic design concept for North Sea dikes were summarized in Kortenhaus (2003). Based on a literature review the results were summarized in a table where for every parameter the mean value \( \mu \), the standard deviation \( \sigma \), the coefficient of variation \( \sigma' \), the type of distribution as well as the related references were given.

Furthermore, in Kanning & Van Gelder (2007) an analysis of uncertainties and the influence of uncertainties on the reliability of flood defence systems is described. This report aimed to identify all uncertainties that influence the reliability of a dike ring systems and to find out which uncertainties contribute most to the probability of failure.

### 2.4 Failure Probability Calculations

Considering the strength and the load as random variables with the probability distributions for strength \( F_R(x) \) and loading \( f_S(x) \) the probability of failure is given by (see Fig. 2.4):

\[
P_f = \int_{-\infty}^{\infty} F_R(x)f_S(x)dx
\]

(0.5)

with:
- \( P_f \) = probability of failure
- \( x \) = assumed value for loading
- \( F_R(x) \) = probability that the strength \( R \) is less than \( x \)
- \( f_S(x) \) = occurrence probability that the loading \( S \) lies close to \( x \)

The probability of failure is given as the product of the probabilities of two independent events summed over all possible occurrences. It is assumed that the loading has a value \( x \). Hence, the probability of this occurring is given by \( f_S(x)dx \) (i.e. the probability that the loading \( S \) lies close to \( x \), within an interval of length \( dx \)). Failure will occur if the strength \( R \) is less than \( x \). Assuming that \( F_R(x) \) is the probability that the strength \( R \) is less than \( x \), so the integral is the probability that for a given load \( S = x \), failure will occur. The total probability of failure is obtained by summing over all possible values that \( x \) can take.
Generally there is no analytical solution for determining the probability of failure (multi-dimensional integral). Therefore, approximate solutions and simulation solutions are used. These solution procedures in reliability theory are classified in ‘Levels’ of sophistication according to their accuracy and complexity as summarised in Reeve (2010):

**Level 0**

**Traditional methods that use characteristic values of strength and loading.**
In the traditional design approach, characteristic values of strength (R) and load (S) are used to ensure that R is sufficiently greater than S to meet the design requirements.

**Level 1**

**Semi-probabilistic method (reliability concept, standard design methods)**
S and R are assigned characteristic or mean values. Partially safety factors are assigned to each of the variables of the major loading and strength variables to account for uncertainty in their value. In standard structural design, partial safety factors are provided in building codes and the like, and are based on a large body of designs and tests.

**Level 2**

**Probabilistic approximation (FORM, SORM, RSM)**
Approximation of the distribution functions of the strength and load variables to estimate the integral of the failure probability. Level II methods have been further subcategorised as first-order risk methods (FORM), and second-order risk methods (SORM), depending on the order of the approximation to the reliability function.

**Level 3**

**Exact probabilistic estimation (Monte-Carlo Simulation, numerical integration)**
The integral of the failure probability is directly estimated or through numerical simulation techniques.
2.5 Fault Tree Analysis

A fault tree can be used to analyse the reliability of an element or a system in a logical manner. A fault tree is a description of the logical interconnection between various component failures and events leading to the total failure of the analysed element or system. The fault tree is constructed from events of failure mechanisms which are connected by gates. Gates are logical operators such as AND, OR, or IF-gates. The highest level of event is defined as TOP event which corresponds to the overall failure of the analysed system or structure as a whole. The definitions and symbols of gates in fault tree analysis are given in Fig. 2.5. In the following the principles of a fault tree analysis are summarized:

- The highest level of event is defined as TOP event which corresponds to the overall failure of the analysed system or structure and represents the essential function of the structure. Within reliability analyses of flood defence structures, the TOP event is often defined as flooding of the hinterland. All failure mechanisms are linked together leading to the TOP event.

- All events of failure mechanisms are represented by a box within the fault tree.

- Events of failure mechanisms could occur several times and could lead to different consequences.

- The events of failure mechanisms are linked by gates. The gates define the type of connection between the single events. The following gates have been applied within a fault tree analyses of dikes
  
a) logical "OR " gate (box with letter "O "): the next level of the tree can only be reached if one of the connected events of this gate fails (Series system: the failure of one event automatically leads to the failure of the whole system)

b) logical "AND " gate (box with letters "A "): the next level can only be reached if all of the connected events of this gate fail (Parallel system: all events must fail before the whole system fails)

c) logical "IF" gate (box with letter "I "): the next level can only be reached if the initial condition of the event defined by the gate are fulfilled.
An overview of calculation methods of determining failure probabilities within fault tree analyses of parallel and series systems is given in Tab. 2.1.

<table>
<thead>
<tr>
<th>gate</th>
<th>parallel system</th>
<th>series system</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum limit</td>
<td>( P_f = \min(P_i) )</td>
<td>( P_f = \sum_{i=1}^{n} P_i )</td>
</tr>
<tr>
<td>totally dependent</td>
<td>( P_f = \min(P_i) )</td>
<td>( P_f = \max(P_i) )</td>
</tr>
<tr>
<td>totally independent</td>
<td>( P_f = \prod_{i=1}^{n} P_i )</td>
<td>( P_f = 1 - \prod_{i=1}^{n} (1 - P_i) )</td>
</tr>
<tr>
<td>minimum limit</td>
<td>( P_f = 0 )</td>
<td>( P_f = \max(P_i) )</td>
</tr>
</tbody>
</table>

The calculation of probabilities of failure from fault trees usually requires some assumptions about the mutual exclusivity of failure mechanisms (i.e. failure arises from one or other failure mechanisms, not a combination of them) and independence between members of the system.

In Reeve (2010) a number of difficulties are listed that arise when trying to apply standard fault tree analysis to flood defence structures:
• There is generally insufficient data to assign failure probabilities to individual components with any degrees of confidence because the number of failure is small.

• Fault trees are essentially binary in character, that is, components either work or fail. However, components of a hydraulic structure undergo various degrees of damage in response to loading of different severity and, even when damaged, can even provide a reduced level of protection.

• The combination of probabilities of different events to obtain the probability of the TOP event requires an assumption that the events are mutually exclusive, that is, failure will occur due to only one of the branches on the tree. For example, it would be easy to assume that the failures of each element of a flood-defence system are exclusive events, which would allow the combined probability to be calculated by adding the individual probabilities. However, it is possible for the elements to fail together. For example, a river embankment and flood gate could fail simultaneously if water levels in the river rose above their crest level. More problematically, during the course of a storm, failure of individual components is often influenced by the occurrence of the failure of a different component. For example, scour at the front toe of the defence is likely to affect the likelihood of failure of the front armour layer. The fault tree approach has difficulty in representing this behaviour.
3 Summary

One of the main tasks within XtremRisK subproject (SP) 2 is to determine the loading and the stability of all components of flood defence systems. Therefore, a reliability analysis of coastal flood defences is performed, i.e. the determination of the failure probability (and thus the flooding probability) which is the first component of flood risk (defined as the product of probability $P_f$ and related consequences $E$ here).

In this report the basic concept of the reliability analysis of flood defences is summarised. Furthermore, an overview of failure mechanisms and associated limit state equations of flood defences such as sea dikes, flood defence walls and coastal dunes are given. The applied limit state equations of flood defence structures are summarized in Tab. 3.1.

In appendices A to C a catalogue of these limit state equations (LSE) is given where each LSE is illustrated by a brief description, a definition sketch, one or more possibilities of LSE, a description of the variables of the resistance and the loading variables and the associated reference.

Furthermore, in appendices D to F a catalogue of fault trees is given. For each flood defence structure the fault tree combining different limit state equations to the TOP-event “flooding” is shown.
### Tab. 3.1: Overview of limit state equations (LSE) applied in XtremRisK

<table>
<thead>
<tr>
<th>No.</th>
<th>LSE Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Non-Structural Failure of Dikes</strong></td>
</tr>
<tr>
<td>1</td>
<td>overflow (functional failure)</td>
</tr>
<tr>
<td>2</td>
<td>wave overtopping (functional failure)</td>
</tr>
<tr>
<td></td>
<td><strong>Failure of Seaward Slope of Dikes</strong></td>
</tr>
<tr>
<td>3</td>
<td>velocity wave run-up</td>
</tr>
<tr>
<td>4</td>
<td>wave driven erosion</td>
</tr>
<tr>
<td>5</td>
<td>wave impact</td>
</tr>
<tr>
<td>6</td>
<td>cliff erosion by wave impact</td>
</tr>
<tr>
<td>7</td>
<td>erosion of revetment armour (rock)</td>
</tr>
<tr>
<td>8</td>
<td>uplift of the revetment</td>
</tr>
<tr>
<td>9</td>
<td>deep slip (Bishop)</td>
</tr>
<tr>
<td></td>
<td><strong>Failure of Landward Slope of Dikes</strong></td>
</tr>
<tr>
<td>10</td>
<td>overflow velocity</td>
</tr>
<tr>
<td>11</td>
<td>wave overtopping velocity</td>
</tr>
<tr>
<td>12</td>
<td>erosion by overflow / wave overtopping</td>
</tr>
<tr>
<td>13</td>
<td>sliding of clay layer*</td>
</tr>
<tr>
<td>14</td>
<td>clay uplift*</td>
</tr>
<tr>
<td>15</td>
<td>deep slip (Bishop)</td>
</tr>
<tr>
<td>16</td>
<td>partial breach</td>
</tr>
<tr>
<td></td>
<td><strong>Sliding and Internal Erosion of Dikes</strong></td>
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<tr>
<td>17</td>
<td>sliding of dike with clay cover (functional failure)</td>
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<tr>
<td>18</td>
<td>piping*</td>
</tr>
<tr>
<td>19</td>
<td>matrix erosion*</td>
</tr>
<tr>
<td></td>
<td><strong>Failure of Dike Top</strong></td>
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<tr>
<td>20</td>
<td>erosion of inner slope &amp; dike top failure*</td>
</tr>
<tr>
<td>21</td>
<td>sliding of inner slope &amp; dike top failure*</td>
</tr>
<tr>
<td>22</td>
<td>clay uplift of inner slope &amp; dike top failure*</td>
</tr>
<tr>
<td></td>
<td><strong>Non-Structural Failure of Walls</strong></td>
</tr>
<tr>
<td>1</td>
<td>overflow (functional failure)</td>
</tr>
<tr>
<td>2</td>
<td>wave overtopping (functional failure)</td>
</tr>
<tr>
<td></td>
<td><strong>Structural Failure of Flood Defence Walls</strong></td>
</tr>
<tr>
<td>3</td>
<td>deep slip (Bishop)</td>
</tr>
<tr>
<td>4</td>
<td>overturning</td>
</tr>
<tr>
<td>5</td>
<td>piping</td>
</tr>
<tr>
<td>6</td>
<td>hydraulic heave</td>
</tr>
<tr>
<td>7</td>
<td>failure of drainage</td>
</tr>
<tr>
<td>8</td>
<td>bending</td>
</tr>
<tr>
<td></td>
<td><strong>Non-Structural Failure of Coastal Dunes</strong></td>
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<tr>
<td>1</td>
<td>overflow (functional failure)</td>
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<td>wave overtopping (functional failure)</td>
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<td><strong>Failure of Seaward Slope of Coastal Dunes</strong></td>
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<td>erosion</td>
</tr>
<tr>
<td></td>
<td><strong>Failure of Landward Slope of Coastal Dunes</strong></td>
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<tr>
<td>4</td>
<td>overwash</td>
</tr>
<tr>
<td>5</td>
<td>breaching</td>
</tr>
</tbody>
</table>

* composed of several LSE
4 References


