Analysis of coastal flooding and erosion at the German North Sea Coast – two examples

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ABSTRACT: The coastal protection of the German North Sea Coast is characterized by dikes and sandy coasts. By the means of two examples the risks of flooding have been analyzed. The consequences of coastal flooding due to dike failure in the city of Emden have been assessed. The risks of coastal dune erosion will be described at the example of the island Amrum.

1 INTRODUCTION

The intensity and the frequency of offenses of the sea against the coasts increase slowly but steadily, whereas man-made influences accelerate the temporal process of the rising. With an ongoing increasing concentration of values in the coastal lowlands the risk during storm surges also increases. This means that the coastal protection has to be reviewed and – if necessary – improved continuously. Especially the wadden sea and the islands of the North Sea Coast are characterized by an intense morphodynamic, which may lead to sustainable changes of the coast in short terms.

2 THE COASTAL CITY EMDEN

2.1 *Region of interest*

The coastal city Emden is situated in the northwest of Germany at the mouth of the estuary Ems. The city is protected by dikes. Not only because of the Volkswagen factory the harbor of Emden became a turnstile of the European and overseas autocar turnover. The huge damage potential partly near to the dikes requires a well working coastal defence that is also of high importance for the whole region.

2.2 *Water level and sea state statistics*

For the determination of the probability of failure of the coastal defenses in the region under investigation, different elements must be taken into consideration. The assessment of the probability of failure for punctiform protection elements like flood barriers or locks is difficult because of the technical complexity. For dikes there are approaches to calculate different kinds of failure. Past storm surges showed that wave overtopping preceded the dike failure and that this kind of failure should be deemed to be the decisive mechanism. Thus a mathematical description of failure can be done by a comparison of the dike height and the summation of water level and wave run up (von Lieberman 2005). Since there are no adequate time series of sea condition measurements, as a general rule sea state statistics are developed from statistics of water level and wind using numerical models.

2.2.1 *Wind*

The wind conditions responsible for the sea state in the region of interest were estimated with the aid of the European Windatlas (Troen & Petersen 1990). Here comprehensive measurements representative for the German Bight are published. The results were projected to the area under investigation and the probability distribution of the wind was extrapolated for extreme wind velocities assuming a Weibull distribution. It was analyzed how the climate change affects the safety of the coast protection. For this purpose an increase of the wind velocities of 3.8 % was assumed (Schuchardt & Schirmer 2002).

2.2.2 *Water levels*

To create a sea condition statistic it is necessary to know the probability distribution of water levels in addition to wind velocities and wind directions. For the city Emden water levels from the year 1949 to 2003 were available and were extrapolated under the assumption of different probability distributions which resulted in varying probabilities of occurrence. In addition to the calculation of the current failure probability of the coastal defense an assumption of the influence of the global change is given.

2.2.3 *Sea condition*

By means of the sea condition atlas of the Hanover University of Technology the sea condition parameters for a certain point in the region of interest could be calculated depending on the water level, wind direction and wind velocity. For different points at the dike line the wave heights and wave periods were assessed. Since the occurrence probability of the parameters is known, a statistic of the sea condition could be created.

2.3 *Probability of failure*

After creating the statistics of water levels and sea condition the probability of the failure of different dike sections could be assessed. The calculation of the probability of failure, in this case the calculation of the probability of wave overtopping, was done on the basis of the equation

$$p_{Z<0} = \int_0^{2\pi}\int_0^{\infty}\int_{h_d - z_{98\%}}^{\infty} p(Thw, u_W, \gamma_W)\, dThw\, du_W\, d\gamma_W \quad (1)$$

with: u_W = wind velocity [m/s]

γ_W = wave direction [°]

Thw = Tidal high water [m above sea level]

h_D = height of dike [m]

$z_{98\%}$ = wave run up, which is exceeded by 2% of all wave run ups [m]

The limit state function Z is described by the difference of an acceptable wave overtopping rate and a middle overtopping rate.

$$Z = q_{acc} - q_{mid} \quad (2)$$

The acceptable wave overtopping rate was set to $3{\cdot}10^{-3}$ m³/s·m according to the EAK 2002 (Ausschuss fuer Kuestenschutzwerke 2002).

At chosen profiles in the dike line the probabilities of failure were calculated. The area of the harbor was excluded because here a different mechanism of failure is crucial. Figure 1 shows the results of the calculation. The recurrence intervals of failure (the inverse of the failure probability) are very high due to the immense heights of the dikes. Even in case of an increasing tidal high water the recurrence intervals remain on a high level. The effect of increasing wind velocities is low in comparison with an increasing water level (Figure 2). Conspicuous are the different levels of recurrence intervals along the dike line according to different heights and dike geometries. The highest levels are located at the Volkswagen factory (dike-km 135) and at housing areas east of the harbor (dike-km 128).

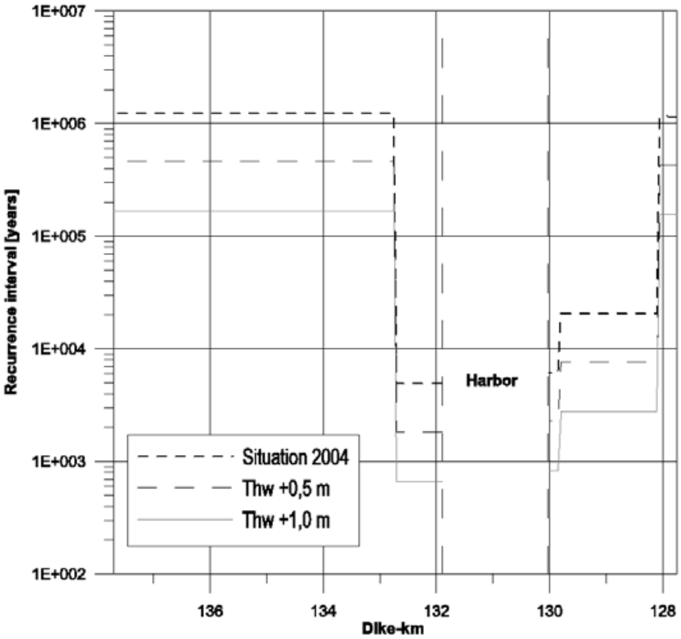

Figure 1. Recurrence interval of dike failure in the region of interest. Situation 2004 and increasing tidal high water.

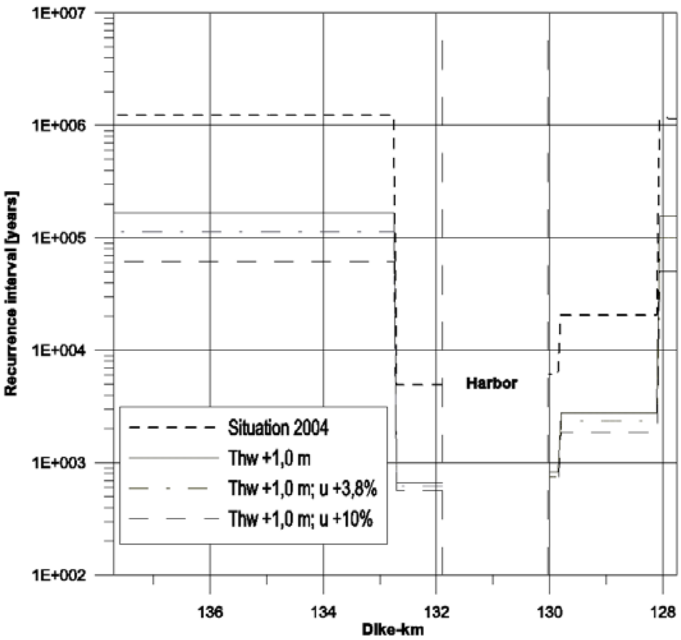

Figure 2. Recurrence interval of dike failure in the region of interest. Increasing tidal high water and wind velocity.

This used approach is a simplified approach in comparison with the method discussed e.g. by Webbers et al. (2002), which uses a joint probability density function (JPDF) to assess the loads.

2.4 *Flood plain*

To assess the potential consequential damage a determination of the flood plain is necessary. For this purpose information about the ground level elevation is required. The flooded area in case of dike failure is estimated, provided that a semicircular broadening of the water occurs. In doing so a middle

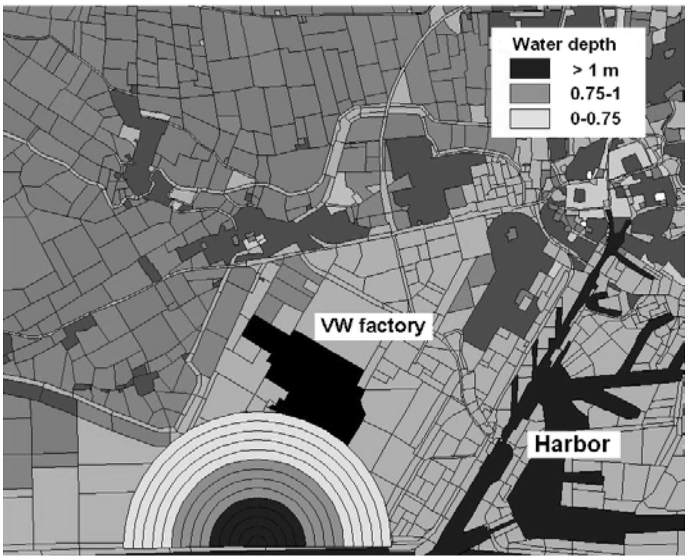

Figure 3. Assessment of the progression of the flood wave. Distance of rings: 100 m.

ground level elevation is assumed and the calculation is done by using Manning-Strickler-Equation. Figure 3 shows the inundation which occurs 60 minutes after a dike failure of 200 m length. This scenario was chosen because of the Volkswagen factory in the direct hinterland of the dike, which means an immense damage potential.

The total flooded area sizes 12 km². By means of damage functions the grade of damage depending on the water depth can be assessed. There different land allocations must be distinguished. To calculate the consequential damage of an inundation in addition to the grade of damage the maximum possible damage must be determined.

2.5 *Damage potential*

The failure of a coastal defense system entails damages of the values in the hinterland. For the region of interest the values of different land allocations were assessed. Considered were financial losses and losses of production. Due to the size of the area under investigation, the assessment of the damage potential was done by using statistics on level of the federal state. These statistics were projected onto the city Emden. The value of line elements, like streets and rails, were asked for at responsible authorities and companies. The major parts were the elements agricultural areas, industrial areas and housing areas. Figure 4 shows the result of the damage potential assessment. The area of the Volkswagen factory is pictured in black. Altogether a damage potential of approximately 15 billions Euros arises.

Using calculated damage potential and assessed water depths the consequential loss can be estimated by means of damage functions.

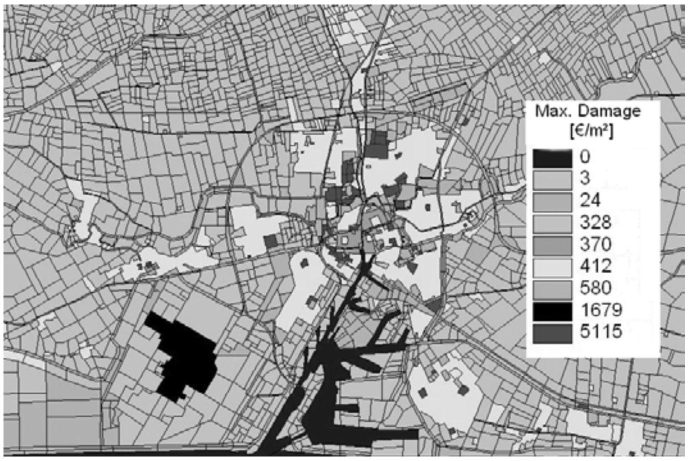

Figure 4. Maximum damage in Euro per m².

2.6 *Risk calculation*

A dike as a part of the coastal defense system has to be designed to protect a particular region of land. The goal is to minimize the construction cost and the expected loss, due to inundation, whereas the crest high and the slope angle are taken as primary optimization variables. Van Gelder & Vrijling (2004) showed that the optimization of a dike design by considering construction cost and corresponding present value of the expected loss (associated with flood damage) is feasible.

For the dike failure scenario like described above the flooded area of 12 km² size gives a consequential loss of approximately 120 million euros. Using the formula

$$\text{Risk} = \text{Probability of failure} \times \text{Consequential loss}$$

the risk can be assessed taking the calculated probability of failure into consideration.

For the examined dike section the risk is 100 euros per year and thus it is extremely low because of the height of the dike. Even in case of an increase of the tidal high water of 1 meter the risk will still be very low with a value of approximately 700 euros per year.

Figure 5 shows the recurrence interval of dike failure depending on the height of the dike. Profile 5 is located to the east of the harbor of Emden near to a housing area. To keep the recurrence interval constant at an increase of the tidal high water of 0.5 meters and of the wind velocity of 3.8%, an upgrading of the dike to 0.60 meters would have been necessary in the year 1997. Due to the dike heightening of 2 meters until the year 1999 the recurrence interval was reduced clearly.

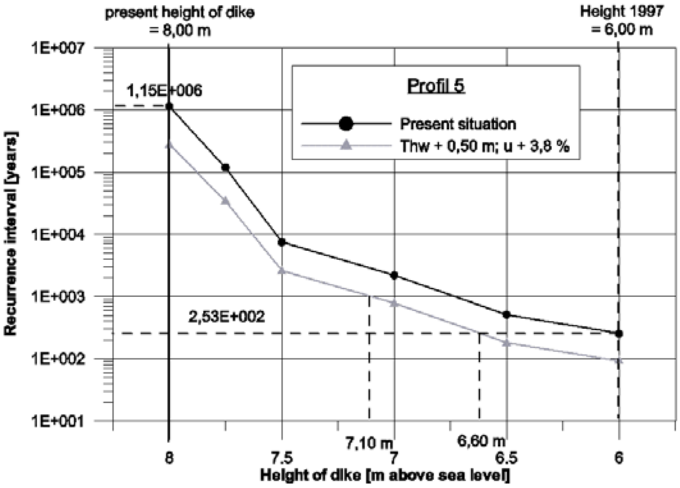

Figure 5. Dependency of recurrence interval of dike failure on dike height.

2.7 *Summary*

The safety of the coastal defense and the existing damage potential of the city Emden were assessed. At the present time the existing coastal defense system guarantees a great safety even in case of increasing water levels due to global change.

The analysis of the damage potential showed that there are immense values in the hinterland so that a sustainable coast protection is of highest importance. Furthermore human lives are in danger in case of dike failure. This is not taken into consideration in any risk analysis but it is of disparate higher meaning.

3 THE ISLAND AMRUM

3.1 *Region of interest*

Amrum (Figure 6) is an island with a size of 20.46 km² and therefore the smallest of the three North Frisian Islands. It borders in the east at the wadden sea and in the west a dune area ranges over the complete length of the island. To the west of this dune belt follows the so-called Kniepsand, a sandbank of 15 km length and 1 km width located a bit above the mean high water. The main purchase of the 2300 inhabitants is tourism. The three villages of the island are located at the eastside.

3.2 *Technical plan for shore protection*

Because of complex morphodynamical processes and the exposed location of the island the coast protection of Amrum is extremely important. At present a technical plan for shore protection on the island is established. Being part of the Integrated Coastal Zone Management (ICZM) information and education of the public is an important aspect. The Hamburg University of Technology, Department of

Figure 6. The island Amrum.

Coastal Zone Management, created a website which describes the coast development and shore protection on Amrum. It was the aim of the project to show the extent of flooding in different areas of the island at various water levels. Both, maximum water levels of historical heavy storm surges and potential water level increases, which may occur due to the global change were taken into consideration. With the help of historical maps and data as well as the comparison of aerial views and cross direction profiles morphological and morphodynamic changes of the island Amrum were illustrated. All buildings with a function in the sense of shore protection were visualised in its function and position.

3.3 *Coast protection*

The dune area is extended over 45% of the island and builds the shore protection at the west side of Amrum. The dunes are of an elevation up to 30 meters above sea level. The preliminary sandbank offers an additional protection in case of a storm surge. During a heavy storm surge in the 1960's parts of the dunes in the north of the island were destroyed. Figure 7 shows the extend of the destruction and the power of the sea. It also clarifies the necessity to observe the dunes and to repair damages with biotechnical coast protection measures. Otherwise a separation of the northern part of the island may occur.

The northeast and the southeast of the island are protected by dikes. Especially the dike in the southeast is of lower quality and may be in danger in case of wave overtopping.

A huger part of the eastside underlies a natural erosion. In this region bigger losses of land occur every year (Figure 8).

The southern hook of Amrum, where the harbor is located, is protected by quay walls and therefore stable in its position.

Figure 7. Destruction of dunes during a storm surge in the 1960's.

Figure 8. Erosion at the eastside of Amrum.

3.4 *Morphological development*

The island Amrum changed during the last centuries under the influence of varying sea levels and heavy storm surges. In the phase of a relatively stabile sea level during the last century a further effect was part of the change of the island's shape: the dislocation of the Kniepsand. The Kniepsand is a continuously changing sandbank. Historical topographic maps and sea charts show that 150 years ago the Kniepsand was only in the southwest part of Amrum connected to the island. Newer maps reveal an approach of the sandbank to the island until it connected with its full length the shore of Amrum. Today it is still moving 50 meters northward every year. In the last years the formation of primary dunes on the Kniepsand occurred. During autumn storm surges they are removed but they offer an additional protection of the dunes.

Further changes of the shape of the island can be observed in the south: Since the 1950's a "nose" is moving towards the south end of Amrum. This development is shown in the Figures 9 and 10.

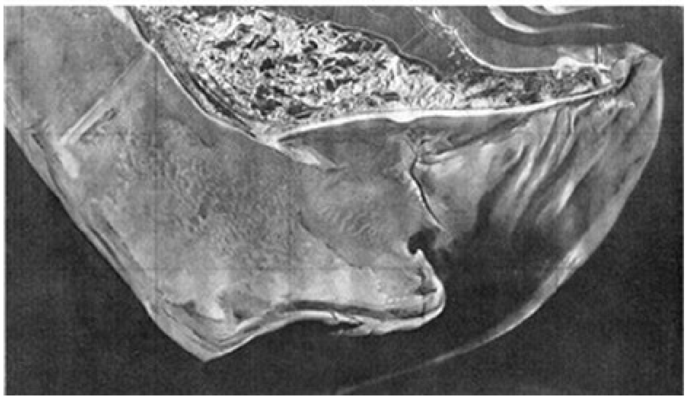

Figure 9. Aerial photo of the southern part of Amrum 1937.

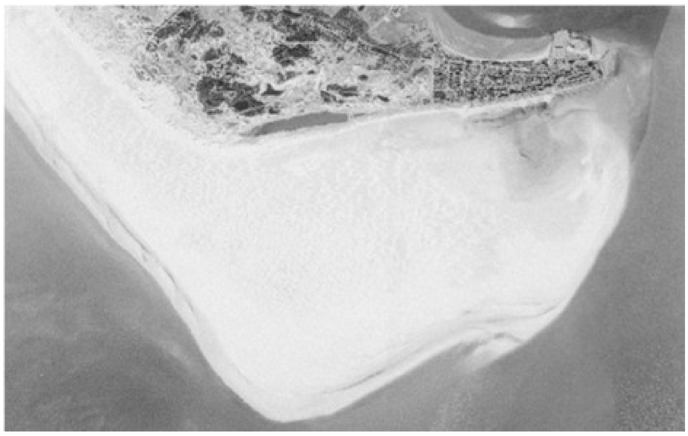

Figure 10. Aerial photo of the southern part of Amrum 2005.

3.5 *Inundation areas*

To assess the potential inundation areas on the island, a static analysis was used. In doing so the ground level elevations and different storm surge levels were intersected in a Geographical Information System. The result was post-processed in a way that "water-puddles" with no contact to the sea were eliminated manually. The mean high water and different storm surge levels were taken into consideration. Additional an increasing of the highest high water due to the global change was included. Figure 11 shows the inundation with the present coast protection system at a water level from the storm surge 1962 plus 1 meter due to a potential sea level rise. The dunes build a relatively safe shore protection system but in the East larger areas are flooded. The dikes in the Northeast and the Southeast are overrun and the danger of a separation of the northern part of Amrum is given.

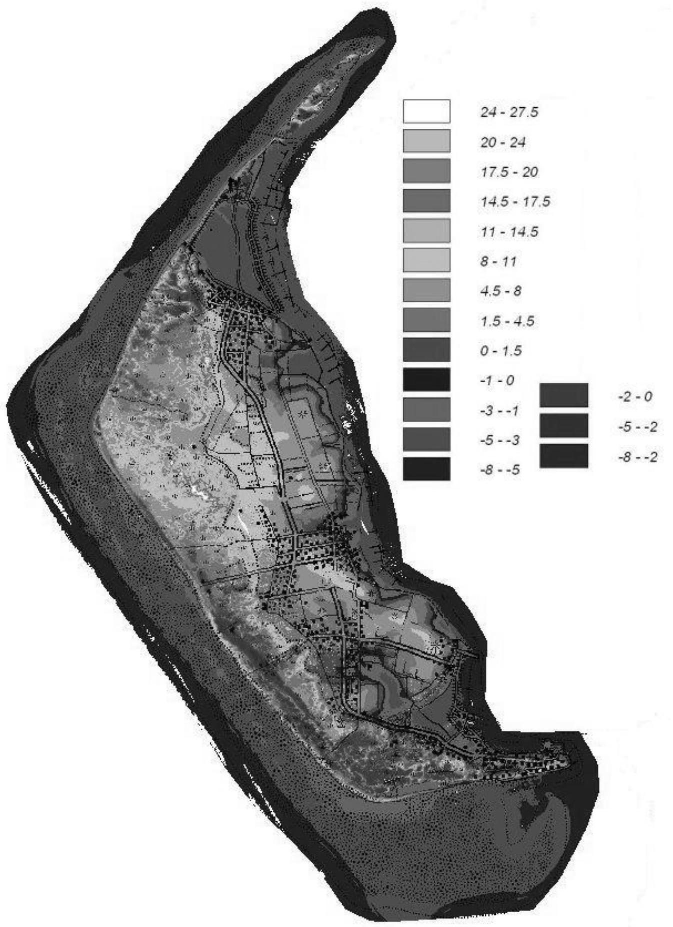

Figure 11. Inundation area at a water stage of 5.15 m above sea level. The elevations indicate the position of the bottom relatively to the water level.

3.6 *Decision Support System*

All results of the survey were summarized in a decision support system which helps to evaluate future civil works, possible erosion scenarios and changes in water levels.

The created system gives a description of the present coast protection and its quality. The high dynamic in the environment of the island is worked out and the large necessity of shore protection is exposed by showing the impacts of heavy storm surges.

On the one hand the developed website is an instrument for the interested and affected public to get information about the coast protection of the island Amrum, on the other hand it is a basis of communication for the decision makers in the authorities.

The decision support system is still being enhanced and can be found on the website of the department of coastal zone management:

www.tu-harburg.de/wb/czm

3.7 *Summary*

Due to its exposed position the island Amrum is characterized by an intensive morphodynamic. The dunes with the preliminary sandbank which build the coastal defense system in the west of the island constitute a comparatively safe system. Problems may occur in the northwest where a heavy storm surge may disconnect the north part from the rest of the island. Furthermore erosion causes troubles at the eastside. The created decision support system summarizes all information concerning the coastal defenses and helps to focus on problems. At the present the safety of the shore protection on Amrum is high but a continuous monitoring is necessary due to large potential inundation areas in case of failure of a defense system.

4 CONCLUSIONS AND RECOMMENDATIONS

The different coastal defense systems at the German North Sea Coast are liable to complex and non-static loads due to changing hydraulic conditions and a changing morphology. Moreover there are various boundary conditions in different regions, e.g. the damage potential in the hinterland. To guarantee a reasonable use of the available financial funds, risk analyses should be applied to assess different measures in coastal protection. A summarization of all available information in a decision support system is sensible, whereas an access of all involved authorities to this DSS is necessary. Furthermore a continuous update should be carried out.

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