Die Küste, 81 (2014), 481-489

Model-Based Verification of Dikes along the West Coast of Schleswig-Holstein

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Summary

Every 10 to 15 years, the German Federal State of Schleswig-Holstein performs a safety check of its sea dikes. The regular check shall ensure that critical changes both to the structure and to the expected hydrological forces as a result of climate change are detected in time. While in the past wave run-up or debris edge measurements were used to determine the necessary wave parameters for the safety check, for the "Coastal Defence Master Plan 2012" of Schleswig-Holstein these parameters were calculated with a numerical wave model. An advantage of this method is that wave data in the required resolution for all dikes are established with a uniform procedure, regardless of natural data with frequent measurement errors. In the present paper this procedure is exemplified for the island of Pellworm.

Keywords

Sea dikes, safety check, wave model, design wave

Zusammenfassung

Alle 10 bis 15 Jahre führt das Land Schleswig-Holstein eine Sicherheitsüberprüfung seiner Seedeiche durch. Durch die regelmäßige Überprüfung soll sichergestellt werden, dass kritische Veränderungen sowohl am Bauwerk als auch bei den zu erwartenden Belastungen infolge der Klimaänderung rechtzeitig erkannt werden. Mussten in der Vergangenheit die für die Überprüfung erforderlichen Seegangsparameter noch aus Wellenauflaufmessungen und Treibselmessungen ermittelt werden, so wurde für den „Generalplan Küstenschutz 2012" des Landes Schleswig-Holstein der Seegang mit einem numerischen Seegangsmodell berechnet. Das hat den Vorteil, einen an allen Deichstrecken mit einem einheitlichen Verfahren ermittelten Seegang in der erforderlichen Auflösung zur Verfügung zu haben, unabhängig von oftmals mit Messfehlern behafteten Naturdaten. Am Beispiel der Insel Pellworm wird das Verfahren vorgestellt.

Schlagwörter

Seedeiche, Sicherheitsüberprüfung, Seegangsmodell, Bemessungsseegang

Contents

1 Introduction

Schleswig-Holstein, the German Federal state between the North Sea and the Baltic Sea, has a coastline of 1105 kilometers in total. Nearly 430 km of that coast are protected by so-called state dikes (Fig. 1), a further 96 km by so-called regional dikes. State dikes have an accordingly high protective standard, safeguarding the hinterland against storm surges, often in interaction with other sea defenses (second dike line) or other flood protection systems (MELUR 2012). In general, regional dikes have a lower safety standard.

The west coast of Schleswig-Holstein is characterized by low lying marshland. Over a length of 228 km, the west coast is protected by state dikes, with a few exceptions. A further 131 km of state dikes can be found on the islands (71 km) and along the Elbe Estuary (60 km). In contrast, on the eastern coast of Schleswig-Holstein there are, with a total of 71 km, comparatively few state dikes.

Figure 1: Overview of Schleswig-Holstein with state dikes (black lines). (LKN-SH (Schleswig-Holstein Agency for Coastal Defense, National Park and Marine Conservation)).

The state dikes in Schleswig-Holstein are inspected regularly every 10 to 15 years regarding their protective standard, the last time in 2011 (MELUR 2012). For this dynamic dike safety system, established in the Coastal Defence Master Plan 2001, wave overtopping is used as a safety criterion. In the past, the regional run-up heights of waves were derived from debris edge measurements. The approach used from 2001 on has the advantage that, in addition to the water level and sea conditions, the local wave attack direction and the geometry of the seaward slope are also considered.

Allowing for the fact that small scale overtopping does not affect dike safety, Schleswig-Holstein accepts a maximum wave overtopping of two liters per meter and second. This value applies to dikes with an intact grass cover on the inland slope. For covered dikes, such as asphalt dikes, higher values are tolerated. If the calculated overtopping rate exceeds the permitted limit, dike strengthening becomes necessary.

For the Coastal Defence Master Plan 2001, an in-house developed method was used to calculate the wave parameters at the dike toe from wave run-up and debris edge measurements. These parameters were then interpolated to the entire dike stretch. As it turned out later, this method has some weaknesses. On the one hand, the debris edge measurements are not sufficiently reliable and on the other hand, the extrapolation over larger stretches is problematic (PROBST 2004).

The calculation of the wave overtopping rates has been carried out since 2008 on the basis of the deterministic method according to EUROTOP (2007). In the meantime, the EAK-method (EAK 2002) was also used, which, however, in comparison had lower overflow rates. Since then, the wave parameters required for this method are generated using a numerical wave model.

2 Design wave evaluation

The evaluation of the wave parameters for the safety check of the state dikes in 2012 was done using the spectral wave model SWAN (Simulating Waves Nearshore). The suitability of SWAN for the determination of sea states during storm events on the west coast of Schleswig-Holstein has already been described by MAI (2002) and NIEMEYER and KAISER (2003).

In the SWAN-simulations, all available physical processes that affect the sea in the computational area were considered. These include the energy input by wind, refraction, shoaling, depth-induced wave breaking and white capping, the nonlinear interactions between the waves (triad and quadruplet interaction) and bottom friction.

If the spatial resolution is high enough, SWAN can also take into account the influence of diffraction. Due to the size of the study area, however, this option could not be applied. In areas that are not exposed to the main attack direction of the swell, additional wave energy can be entered by diffraction. This effect must be considered when determining the design wave for areas which are shaded from wave action.

As a worst case scenario for the safety check of the dikes, a combination of a reference storm surge water level and the maximum possible wave was defined.

3 Boundary condition storm surge level

The storm surge water level used in the simulation was determined using a newly developed method which is based on the non-stationary and regional probability analysis (MELUR 2012). The resulting reference water level corresponds to a water level that statistically occurs once every 200 years (RHW200). Therefore, for each dike section a separate model run is required.

4 Boundary condition wind

Investigations of storm surge water levels and corresponding wind speeds and wind directions on the west coast of Schleswig-Holstein led to the conclusion that for the occurrence of the wind set-up in the case of reference water level the sector between SW and NW can be defined as the significant wind direction.

Regional wind measurements on the west coast were used to determine the highest expected wind speeds for these wind sectors. For example, the highest measured wind speeds (for the period from 1969 to 2011) and their directions are shown in Tab. 1, taken during a storm tide at the wind gauge on Hallig Hooge in the southern North Frisian Wadden Sea.

Table 1: Highest measured wind speeds for different wind directions during a storm tide at the wind gauge Hallig Hooge (DWD) for the period 1969-2011 (*gauge Husum (WSA Tönning); NHN: normal height null).

date	name	swl *	wind	
		[NHN+m]	ϴ [-]	u [m/s]
24.11.1981	-	5.15	SW	26
08.01.2005	Freddy	3.46	WSW	25
03.12.1999	Anatol	5.37	W	29
03.01.1976	Capella	5.61	WNW	28
10.01.1995	-	4.37	NW	22

Based on these studies, the highest wind speed was determined to be 32 m/s for wind directions in the SW to NW sector. To prevent the risk of an underestimation of the design wave, the chosen wind speed value was set even higher than the measured values.

The choice for the highest wind speed on the west coast of Schleswig-Holstein has already proven to be true and not too high. During storm "Christian" on 28 October 2013, for example, the measured wind speed at the Hallig Hooge gauge was nearly 32 m/s, blowing from WSW.

5 Simulations

Due to the size of the study area, the number of dike sections and differing accuracy requirements on the model results, the simulations were performed with nested models with different expansion and grid width.

The model bathymetry in each case was based upon the latest available survey data. Fig. 2, for example, shows the procedure for the island of Pellworm.

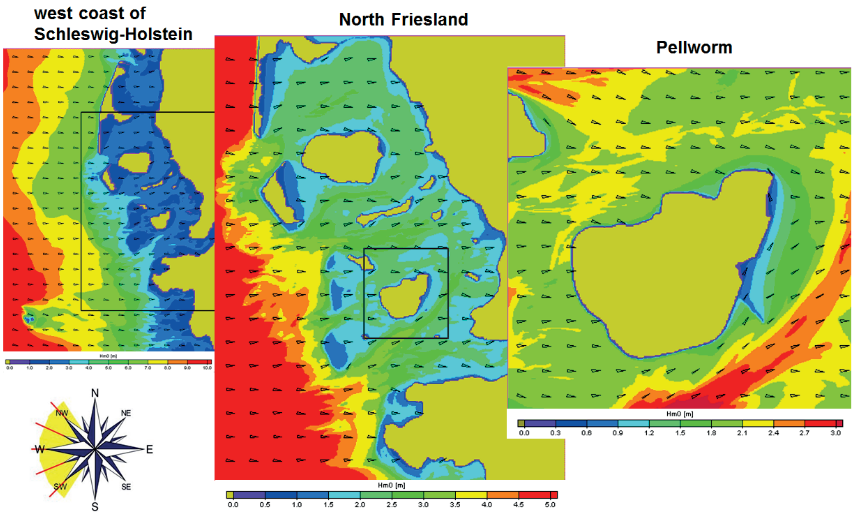

Figure 2: Simulated significant wave height and mean wave direction in the nested models for the scenario "wind from west". (LKN-SH).

The boundaries of the parent model area (German Bight model) were set in such a way that the wave heights and wave periods at the edge had no influence on the simulated wave parameters in the area of the detailed models (dike section models). The waves in the Wadden Sea are already affected by the local wind. Therefore, the incoming waves only have a limited impact on this area.

Stationary simulations were performed, i.e., the water level and the wind field were assumed to be a temporal and spatial constant. The decisive wind sector between SW and NW was subdivided into five wind sections with an angle of 22.5 ° each. For each regionally different reference water level (RHW200), a total of five model runs had to be carried out.

6 Wave parameters at the dike

The calculation of wave run-up and wave overtopping by EUROTOP (2007) requires the wave parameters directly at the dike toe (The dike toe on dikes with a foreshore is the transition from the dike slope onto the foreshore, on dikes without a foreshore it is the transition onto the intertidal flats). On the west coast of Schleswig-Holstein, the elevation of the foreshore can reach up to NHN + 2 m. Thus, the dike toe is the decisive point for calculating the sea state.

Due to the fact that the safety check at the west coast of Schleswig-Holstein was usually performed at dike profiles with intervals of 500 m, the wave parameters (from the model calculations) at the dike toe were required for these profiles.

The wave model SWAN provides the option of producing wave parameters at specified altitudes on defined profiles. If it is assumed that the elevation of the dike toe of the dike without a foreshore lies at NHN +1 m, while the toe of a dike with a foreshore is located at NHN +2 m, the authoritative points can be automatically determined. For these points the wave parameters can be produced.

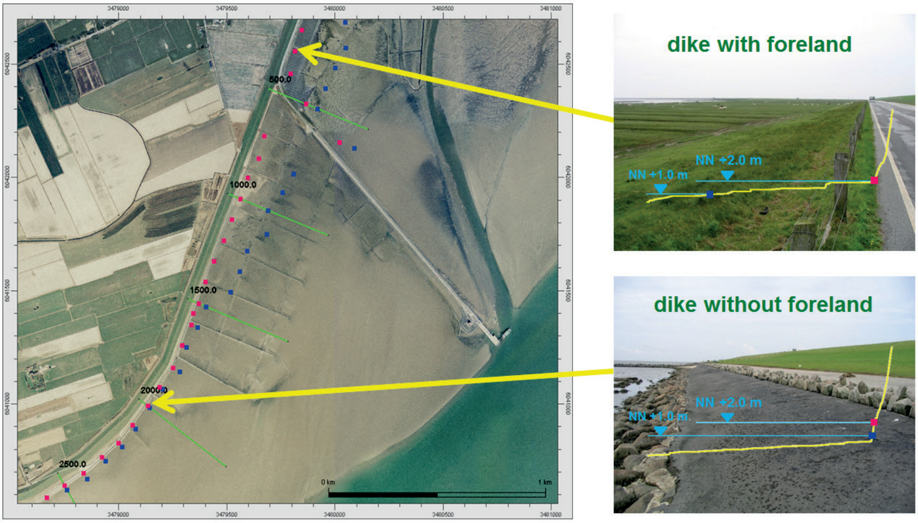

Figure 3: Locations for the design wave at the east side of the island Pellworm (red: NHN +2 m; blue: NHN +1 m; aerial photograph 2005). (LKN-SH).

Fig. 3 shows the exemplary result of this procedure for the east side of Pellworm with tidal flats, a tidal channel called Norderhever, a dam to the ferry dock and the harbor entrance to the old port of Pellworm. South of the dam to the deep-water ferry dock, the dike has no foreland over a distance of more than 1 km. At close range north and south of the dam, however, foreland has formed since the dam's completion in 1991.

As a criterion for the determination of the highest sea state from the simulation results for different wind directions, the amount of the expected wave run-up was used. The choice of the highest wave parameter, i.e. the worst combination of wave height, wave period and wave direction at each location of the dike profiles, was extracted from five results using the wave run-up formula by EUROTOP (2007).

7 Results

Fig. 4 shows the design wave, which was determined on the basis of the described simulations, for the state dike of the island of Pellworm. For the calculation of wave overtopping by EUROTOP (2007) the parameters significant wave height (H_{m0}) and average wave period ($T_{m-1.0}$) are needed. As expected, the design wave of the dike section at the south side of Pellworm is the largest. At the dike sections with a foreshore, the damping effect of the foreshore on the design wave is clearly noticeable.

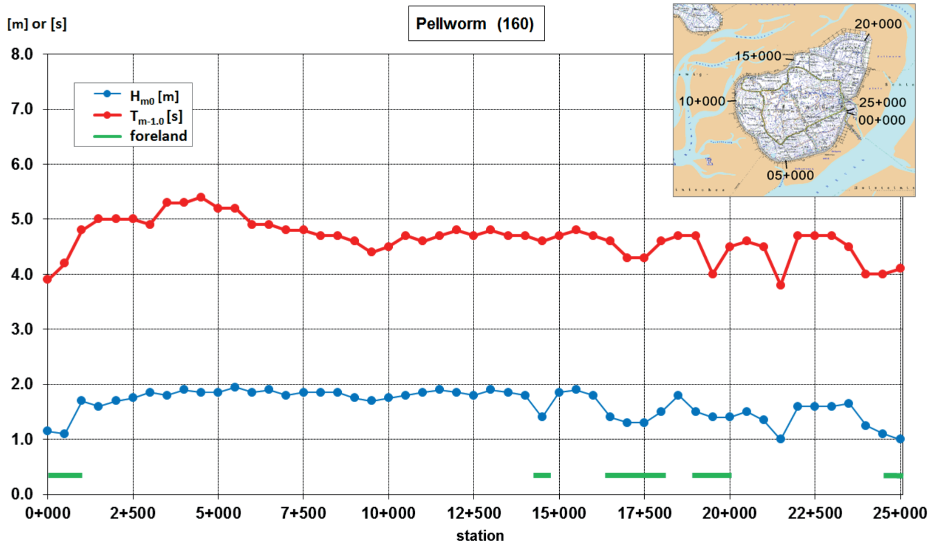

Figure 4: Model-based design wave for the safety check of the state dike of the island of Pellworm. (LKN-SH; top right: DTK50-V LVermGeo SH).

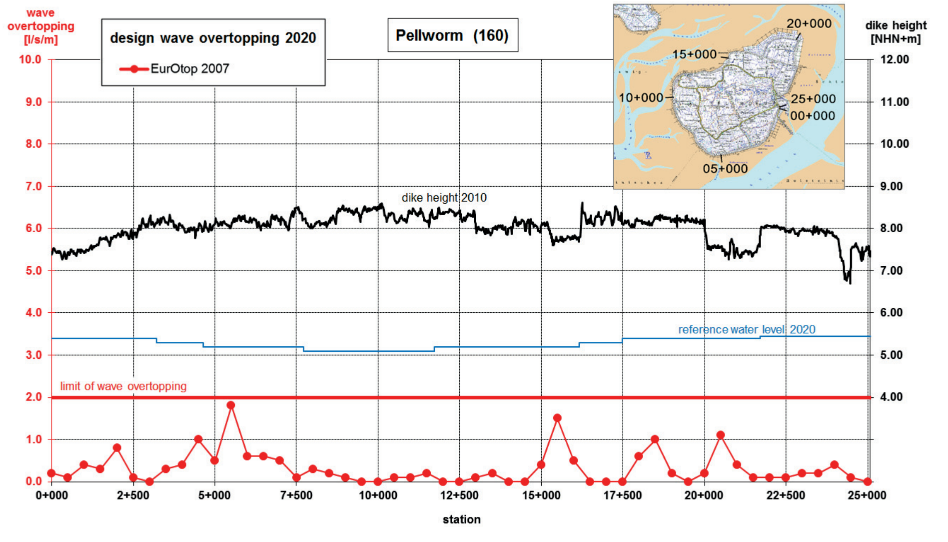

Figure 5: Design wave overtopping for the reference water level RHW200 at the state dike of the island of Pellworm. (LKN-SH; top right: DTK50-V LVermGeo SH).

Simulations of storm events (hindcasts) in the southern North Frisian Wadden Sea have shown that SWAN delivers good results for the wave height, compared to the measured data. The mean wave periods are a bit underestimated in the model. Since only little measured data for storm events is available, no reliable value for the deviation between model and natural period can be currently calculated. Additionally, the magnitude of the differences varies regionally. To avoid any risk of underestimation of the wave period, the model-based periods were applied with a safety factor of 1.25 for the safety check. The results are, therefore, always on the safe side.

The result of the safety check in 2012 for the island of Pellworm is shown in Fig 5. Based on the calculated wave overtopping, the permitted overtopping of 2 l/s/m is not exceeded at any verified dike profile. So from a hydrological point of view, no dike strengthening is required for the island of Pellworm.

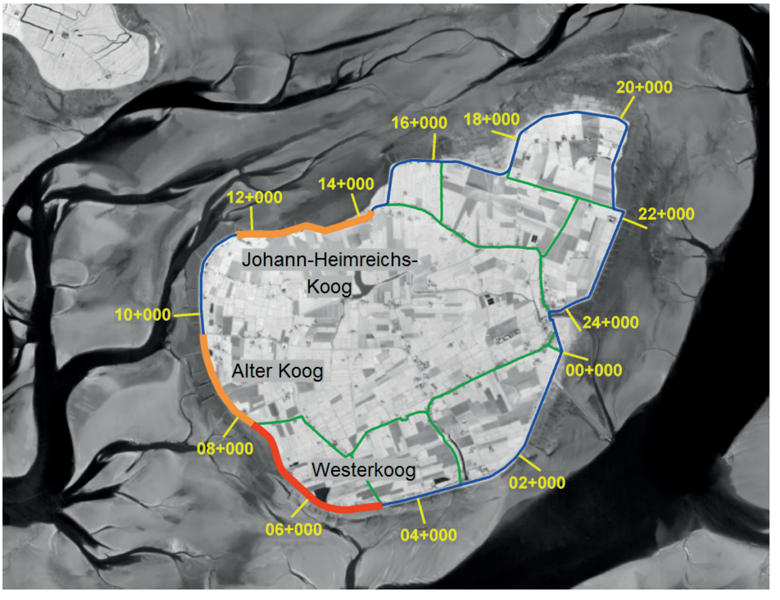

Figure 6: Planned dike strengthening on the island of Pellworm (red: urgent; blue-line: state dike; aerial photograph 2000). (LKN-SH).

However, apart from hydrological criteria, geotechnical (e.g., grass cover, dike material) and other criteria such as the presence of a second dike line determine the safety of state dikes as well. On the basis of these non-hydrological criteria, it was determined in the Coastal Defense Master Plan of 2012 that, for the dike section "Westerkoog", an urgent strengthening is needed over a length of 3.1 km (Fig. 6). Further strengthening campaigns are needed at the sections "Alter Koog" and "Johann-Heimreichs-Koog", respectively, over a total length of 4.5 km.

The safety check of the dikes on the east coast and at the Elbe Estuary was performed in a similar manner.

8 Outlook

Schleswig-Holstein will further investigate the safety status of the regional dikes in the coming years. Therefore, a method on the basis of combined probabilities for water level and waves will be applied.

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