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Sea Dikes in Germany

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1. Introduction

Sea dikes (Fig. 1) and estuarine dikes represent the main coastal defence structure in Germany and protect low lying areas in Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern. More than 2,400,000 people and an area of more than 12,000 km^2 are protected by more than 1,200 km of sea dikes and estuarine dikes in Germany (Tab. 1). The protected economic values are high. In Hamburg, the protected value by estuarine dikes is more than 10,000 Millions of Euro, in Schleswig-Holstein more than 47,000 Millions of Euro.

Tab. 1: Overview of dike lengths, protected area and population in German ferderal states

Federal state	Length of Dikes (primary flood defence line)	Protected area	Protected population
Lower Saxony (incl. islands)	645 km	6,600 km^2	1,200,000
Schleswig-Holstein	527 km	3,800 km^2	345,000
Bremen	74 km	360 km^2	570,000
Hamburg	77.5 km	270 km^2	180,000
Mecklenburg-Vorpommern	150 km	1020 km^2	90,000

Sea dikes have a very long history in Germany. A first citation of seadikes can be traced back to the year 10 (GARBRECHT, 1985). The construction and maintenance of seadikes was firstly organised and managed from around 1150 as a joint agreement between landlords. The history of sea dike design in the mediaeval times was mainly influenced by severe storm surges and the reconstruction after frequent dike failures. The consequences of extreme storm surge disasters and dike failures can still be observed at many locations along the German coast. The islands along the north-frisian coast result from storm surge disasters in 1362 and 1634 and many lakes behind the present dikes have developed due to the scouring process of a breaching dike. Therefore, the crest levels in former centuries correlate well with the

Fig. 1: Modern sea dike in Germany (photo: SCHÜTTRUMPF)

maximum storm surge levels in that times. The memory of the severe storm surges in the past and the consequences is still fresh and not forgotten. As a result of this historical development, the local population has a special attitude towards the safety of sea dikes and the importance of coastal flood defences and coastal protection is well accepted. Nowadays, maintenance and construction of sea dikes are performed by the German Federal States Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern. Each state has a master plan for coastal flood defence and coastal protection to prioritize and to indicate dike reinforcement tasks for the future.

2. History of Sea Dike Design

During the last millennium, many severe storm surges occurred and are reported in several historical chronicles (e.g. BRAHMS, 1754; WOEBCKEN, 1924). The number of fatalities after storm surge disasters in the middle age was high and the consequences for those who survived the flood were severe (Tab. 2). Large areas were flooded, houses and farms destroyed and the fields were rendered useless for agriculture and stock farming. These fatalities, damages and economic losses were caused by flooding through dike breaches. The resistance of dikes in the middle ages and in later centuries against wave attack and high storm surge water levels was low, and many dikes were even overflowed. First dike breaches along the German North Sea Coast with about 20,000 fatalities are reported from a storm surge in 1164. Even if the number of fatalities is uncertain, the importance of this event is obvious for that time.

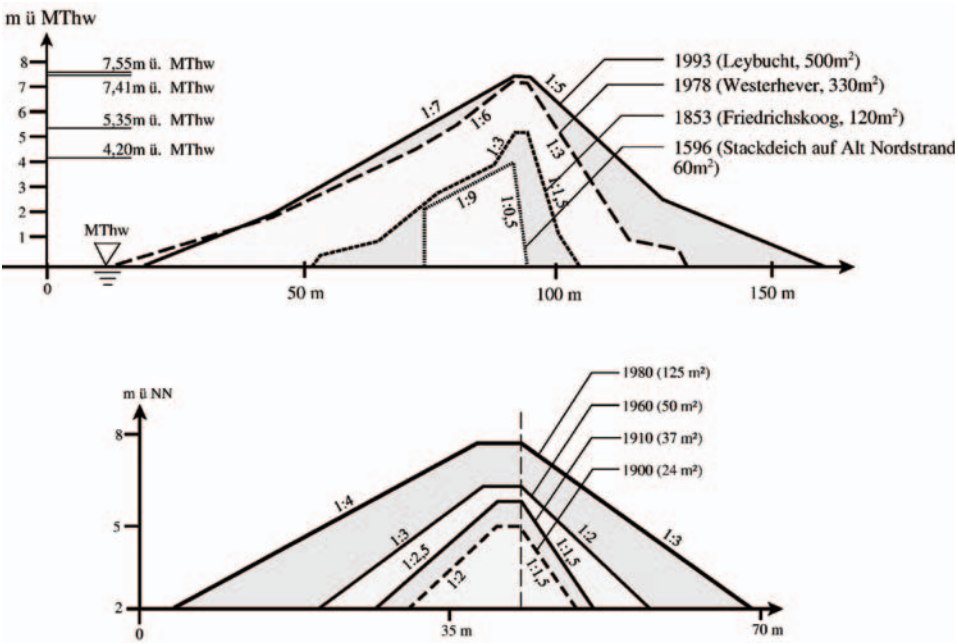

Fig. 2. Evolution of dike profiles in the past (SCHÜTTRUMPF and OUMERACI, 2002) (upper part: sea dikes, lower part: estuarine dikes)

For the years 1362, 1634, 1717 and 1825, more historical storm surge disasters are reported for the Belgian, Dutch, German and Danish coasts. They triggered the development of sea dikes along the coastlines in these countries. Essentially based on experience, sea and estuarine dikes became higher and broader (Fig. 1) over the centuries. First dikes – called 'Stackdeich' (Fig. 2) – were very steep and sometimes vertical on the seaward slope and consisting of a wooden front face.

Compared to modern sea dikes, the crest level was low and able to resist only summer storms. People settled on artificial dwelling mounds to be protected against high winter storms since the sea dikes were not strong enough to protect houses and farms. Observations of the failure mechanisms led to a better understanding of the processes and a better design of sea dikes. Therefore, sea and estuarine dikes became smoother and higher over the centuries. First distinctions between dike failure mechanisms due to breaking wave impacts and dike failures due to wave overtopping are reported from a storm surge in February 1825 (WOEBCKEN, 1925). In addition, unfavourable factors like animal activities in the dike were identified for the first time as a negative effect; burrow animals decrease the stability of the dike under breaking wave impacts or wave overtopping. This knowledge enhanced the design and the maintenance of seadikes. The crest level itself was still designed by experience.

During the storm surge disaster in the Netherlands in 1953, many dike failures and dike breaches occurred (about 139 km of damaged dikes). In 1962 and 1976, about 600 km of damaged dikes and several dike breaches and dike failures along the German coastline, respectively, resulted from severe storm surges in Germany. Fig. 4 shows a breaching estuarine dike near Hamburg during a storm surge in January 1976. A detailed summary of dike failures and dike breaches in Germany is given by SCHÜTTRUMPF and OUMERACI (2002). The

Fig. 3: Stack dike (about 1600) at the dike museum in Büsum (photo: MEIER, 2006)

Fig. 4: Breaching dike (photo: SCHOLZ, 1976)

coastal disasters in recent times changed the design philosophy of sea dikes in Germany. Before 1950, the crest level and the slopes of sea dikes were designed by experience. After that, the crest levels of sea dikes were designed deterministically based on a statistically determined design water level and a corresponding wave run-up height. Experimental investigations were applied to determine the wave run-up height (1st experimental investigation in Germany by HENSEN, 1954) and the wave overtopping rate (1st experimental investigation in

Germany by TAUTENHAIN, 1981). Other failure mechanisms of sea dikes such as the landward slope were considered by experience without taking the individual failure processes into account. Nowadays, it is the objective in Germany to improve the scientific knowledge concerning the probabilistic design of seadikes (KORTENHAUS, 2003). However, the probabilistic design has not found its way into practice yet.

Tab. 2. Storm Surge Disasters in the Southern North Sea (WOEBCKEN, 1924; KRAMER, 1992; JENSEN, 2000)

Date	Area	Remarks	Date	Area	Remarks
about 340 B.C.	Cimbrius Flood		26.2.1625	Total Southern North Sea Coast	Shrove Tuesday flood. Ice flood
17.2.1164	Total Southern North Sea Coast	First Julianen-flood. One of the first severe storm surges after construction of the first seadikes. About 20 000 fatalities between Rhin and Elbe river	11.10.1634	West coast of Schleswig-Holstein	Very severe storm surge and many eye-witness reports. At least 8 000 fatalities
16.1.1219	West- and East Frisia (The Netherlands)	First Marcellus-flood. About 36 000 fatalities. An eye-witness report exists.	22.2.1651		Petri-flood
14.12.1287	Total Southern North Sea Coast	Lucia-flood. Creation of the Dollart between the Netherlands and Germany. 50 000 fatalities	12.11.1686	The Netherlands and Germany	Martin-flood
23.11.1334	From East Frisia to Flanders	Clemens-flood	24.12.1717	Total Southern North Sea Coast	Christmas flood. 6 000 km² land flooded
16.1.1362	Total Southern North Sea Coast	Second Marcellus-flood. Creation and Extension of Jadebusen, Dollart, Harle, Ley-bay. End of north-frisia – mainland is transformed into an island area in the wadden sea. About 100 000 fatalities	31.12.1720/ 1.1.1721	Total Southern North Sea Coast	New Year Flood
9.10.1374 and 1377	East Frisia, Oldenburg	First and Second Dionysius-flood.	3./4.2.1825	Total Southern North Sea Coast	February Flood. Large areas flooded. About 800 fatalities. Many eye-witness reports
1400	Frisia	Frisia Flood	1./2.1.1855	Total Southern North Sea Coast	January Flood
18.11.1421	East England and The Netherlands	Elisabeth-Flood	13.3.1906	East Frisia, Oldenburg	March Flood
1.11.1436	Total Southern North Sea Coast	All Saints Flood	1.2.1953	The Netherlands and England	Netherlands Flood. Very Severe Flood in the Netherlands with about 1850 fatalities, many dike breaches and large flooded areas

6.1.1470	Total Southern North Sea Coast	Epiphany Flood	16./17.2.1962	Total Southern North Sea Coast	Second Julianen-Flood. Many dike failures and dike breaches. Heavy damages in Hamburg. About 315 fatalities in Hamburg
26.9.1509	East Frisia, The Netherlands	Cosmas- and Dami-anflood	Nov./Dez. 1973	Total Southern North Sea Coast	5 severe storm surges in a short time
16.1.1511	East Frisia, Oldenburg	Antonius-flood. Ice-Flood	3.1.1976	Total Southern North Sea Coast	Many Dike Failures but no severe conse-quences
31.10/ 1.11.1532	Total Southern North Sea Coast	Second All Saints Flood. Several thou-sand fatalities. The height of this strom surge is delivered.	24.11.1981	Elbe and west coast of Schles-wig-Holstein	November Flood
1.11.1570	Total Southern North Sea Coast	Third All Saints Flood. Between 9 000 and10 000 fatalities between Ems and Weser	4.12.1999	Elbe, west coast of Schleswig-Holstein and Denmark	Dike Breaches in Southern Denmark
1572		Grain Flood			

3. Modern Sea Dikes in Germany

The construction of sea dikes in Germany differs from federal state to federal state resulting from the local topography, from the availability of different soils, from the local sea states and experiences. A comparison of the different dike elements for the different federal states is shown in Tab 3.

Tab. 3: Typical values for dike elements in the different German states (EAK, 2002)

	Lower Saxony (North Sea)	**Schleswig-Holstein (North Sea)**	**Hamburg (Elbe estuary)**	**Schleswig-Holstein (Baltic Sea)**	**Mecklenburg-Vorpommern (Baltic Sea)**
Seaward Slope	1:6	1:6 to 1:10	1:3	>1:6	1:3 to 1:6
Thickness clay (Seaward slope)	1.3 to 1.5 m	1.0 m	1.5 to 2 m	1.0 m	0.5 to 1.2 m
Crest width	3 m	2.5 m	3 m	2.5 to 3 m	3.0 to 3.5 m
Landward Slope	1:3	1:3	1:3	1:3	1:2 to 1:3
Thickness clay (Landward slope)	≥ 1.0 m	0.5 m	> 1.3 m	≥ 0.5 m	≥ 0.5 to 0.7 m

Two different types of sea dikes can be distinguished (Fig. 5). Type 1 has a wide foreland at an elevation above MHW to protect the dike toe. At storm surge water levels, the high foreland reduces the incoming wave parameters by wave breaking. The width of the foreland can reach several hundred meters. At normal tides, no water, waves or currents affects the dike toe. Thus, no revetment is needed to protect the dike toe. If a smooth slope is not possible due to place constraints, a light revetment is recommended. If no foreland protects the dike, a heavy revetment at the toe of the dike is recommended (Type 2). These revetments are often constructed with a slope 1:3, a toe embedded in the sea bed to avoid scouring and a crest reaching a height of about 1.50 m to 2.0 m above MHW. Usually, an asphalt or concrete berm is located landward of the crest of the revetment. Berms constructed 1.0 m to 2.0 m above MHW with a width of up to 3.0 m often serve as service roads.

The seaward slope of a dike can differ between 1:3 (some estuarine dikes and Baltic Sea dikes without heavy wave loads) and 1:7 (at very exposed locations along the North Sea coast). In general, a grass- covered 0.5 m (Baltic Sea) up to 2.0 m (North Sea dikes) thick clay layer is preferred to avoid erosion and scouring due to wave loading. The quality of the clay is defined in EAK (2002) and in Tab. 4. Some dikes are protected by asphalt or concrete layers, but, generally, grass covered dikes merging into the landscape are preferred. Nowadays, the core of a dike consists of sand with a drainage system towards a trench at the landward toe.

Tab. 4: Critical limits for clay for cover layers of dikes (EAK, 2002)

Soil properties	limits		
	Well suited	suited	Limited
Type of soil	Clay	Sandy clay	Very sandy clay
Percentage of clay	20–40	15–20	10–15
Percentage of sand	10–40	25–50	30–50
Flow limit	35–70	30–55	25–40
Plasticity index	20–45	15–20	10–15
Water content	25–60	25–50	25–45
Dry bulk density	1.10–1.45	1.15–1.50	1.25–1.55
Undrained shear strength	≥ 25	≥ 30	≥ 40
Organic matter	≤ 10	≤ 10	≤ 5

The crest of a sea dike or an estuarine dike in Germany has a width of 2.0 m to 3.5 m to allow vehicles or pedestrians traffic. The crest is slightly sloped to enable overtopping water or rain to flow landwards or seawards without infiltration.

The landward slope has to fulfil geotechnical aspects (no sliding) and erosion or infiltration due to wave overtopping should be avoided. Besides, harvesters should be able to drive on the landward slope. Therefore, landward slopes range between 1:2 and 1:5, but most of the existing slopes are constructed with a gradient of 1:3.

A berm with a width of up to 10 m with a 3 m to 4 m wide road is situated at the toe of the landward slope. This permits heavy vehicles to drive along the dike even during very severe storm situations. The landward berm is located about 0.5 m to 1.0 m above MHW to ensure trafficability even when the low lying areas are flooded during extreme situations.

Finally, an inner ditch is constructed at the toe of the landward berm to collect drained water or rain.

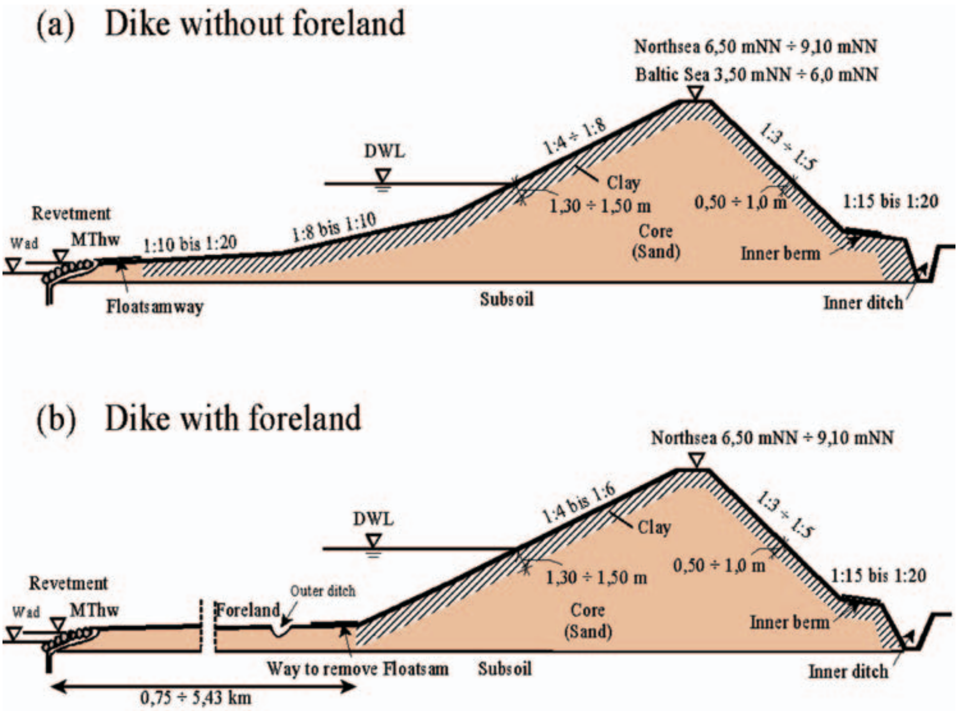

Fig. 5: Typical dike profiles in Germany (SCHÜTTRUMPF, 2001)

4. Crest Level Design of Sea Dikes

Different design philosophies are practised in the German federal states (Fig. 6). Lower Saxony and Bremen have adopted the a-b-c-d-method for seadikes. The design water level is calculated based on the mean tidal water level (a), the difference between the highest spring tide water level and mean high water level MHW (b), the difference between the highest water level (HWL) and MHW (c) and the sea level rise (d). This water level is compared to a water level based on the reference method. The water level based on the reference method is the highest ever observed water level plus a safety margin. The maximum of both methods is used as the design water level for sea dikes in Lower Saxony and Bremen.

This method, however, cannot be used for estuarine dikes in Lower Saxony nor in Bremen and Hamburg because of the influence of the river discharge (Weser and Elbe), a number of construction measures along the estuary (e.g. dikes and barriers) and fairway adaptations in the past. Due to the inhomogeneity of the water level records in the estuaries, the design water level for estuarine dikes in Bremen, Hamburg and Lower Saxony is calculated based on numerical simulations for an undisturbed reference gauge. Finally, a wave run-up height is added to the design water level for sea dikes and estuarine dikes in Bremen, Hamburg and Lower Saxony.

Different methods to determine the design water level are also used along the west coast of Schleswig-Holstein. The design water level should fulfil three conditions. It should (a) have an occurrence probability of 1 in 100 years with respect to the year 2100 (statistical method), (b) not be lower than the ever observed highest water level (reference method) and (c) not be lower than a water level calculated from the a-b-c-d-method. In general, the statistical method gives the highest value for the west coast of Schleswig-Holstein.

Along the east coast of Schleswig-Holstein the reference method is adopted based on an extreme storm surge in 1872 which has never been exceeded. Therefore, the water level from 1872 plus 0.5 m to account for sea level rise is used along the east coast or Baltic Sea coast of Schleswig-Holstein. Finally, a design wave run-up height is added to the design water level along the west and the east coast of Schleswig-Holstein. In addition, a critical mean overtopping rate of 2 l/(sm) should not be exceeded.

The reference method with respect to the extreme storm surge in 1872 is also used along the Baltic Sea coast of Mecklenburg-Vorpommern. An additional value with a range between 0.15 m and 0.25 m, which is to account for sea level rise, is considered. The wave run-up height is added to determine the crest height.

The wave run-up height is calculated in all Federal States according to the "Guidelines and Recommendations for the Design of Coastal Structures" (EAK, 2002).

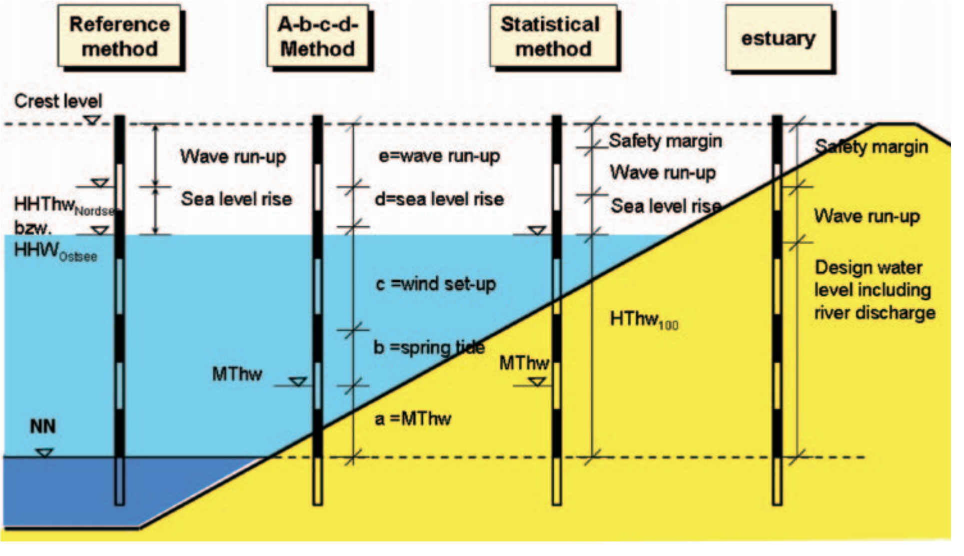

Fig. 6: Methods to calculate the design water level in Germany

Nowadays, it is recommended to apply the European Overtopping Manual (PULLEN et al., 2007) for wave overtopping analysis, which has been set-up in a joint project between the Netherlands, United Kingdom and Germany.

5. Future Aspects of Sea Dike Design in Germany

Thirteen working groups were set up by the German Society of Port Engineering (HTG) to identify important research topics for coastal and estuarine areas. Two of these working groups are related directly to sea and estuarine dikes and some important research topics for sea and estuarine dikes were identified. PETERS et al. (2008) highlighted further research topics concerning the geometry of dikes, the interaction of the hydrodynamic processes and the soil properties, the design of seadikes, the monitoring of sea and estuarine dikes and new strategies for a better coastal and storm surge protection of low lying areas. A number of research topics were also identified by KORTENHAUS et al. (2007) related to the probabilistic design of seadikes. KORTENHAUS et al. identified further research related to a better description of the failure mechanisms and the uncertainties for coastal structure design. More sophisticated probabilistic models are required to keep simulation time manageable. These aspects must be included in a software which is easy to use and considers a database of all relevant information. Finally, critical failure probabilities are required.

6. References

BRAHMS, A.: Anfangs-Gründe der Deich- und Wasserbaukunst. Verlag Schuster, Leer, 1767.

EAK: Guidelines and Recommendations for the Design of Coastal Structures. Die Küste, H. 65, 2002.

GARBRECHT, G.: Wasser – Vorrat, Bedarf und Nutzung in Geschichte und Gegenwart. Deutsches Museum Kulturgeschichte der Naturwissenschaften und Technik. Rororo-Sachbuch, 1985.

HENSEN, W.: Modellversuche über den Wellenauflauf an Seedeichen im Wattengebiet. Mitteilungen des Franzius-Instituts. Nr. 5, 1954.

JENSEN, J.: Extremereignisse an Nord- und Ostseeküsten – Ermittlung von Bemessungsereignissen (Extreme Events at North Sea and Baltic Sea Coasts – Estimation of Design Criteria). Franzius-Institute for Coastal Engineering. H. 85. pp. 41–57, 2000.

KORTENHAUS, A.: Probabilistische Bemessungsmethoden für Seedeiche. Promotion am Leichtweiss-Institut für Wasserbau, 154 S., http://opus.tu-bs.de/opus/volltexte/2004/525. 2003.

KORTENHAUS, A.; FRÖHLE, P.; JENSEN, J.; LIEBERMANN, N.; MAI, S.; MILLER, C.; PETERS, K. u. SCHÜTTRUMPF, H.: Arbeitsgruppe B1 „Probabilistische Bemessung von Bauwerken“, Hansa International Journal, 2007.

KRAMER, J.: Entwicklung der Deichbautechnik an der Nordseeküste. in : „Historischer Küstenschutz“. (Herausgeber: DVWK) WITTWER Verlag, 1992.

LSBG: Hochwasserschutz in Hamburg – Bauprogramm 2007. Landesbetrieb Straßen, Brücken und Gewässer, 2007.

MBL: Generalplan Küsten- und Hochwasserschutz. Ministerium für Bau, Landesentwicklung und Umwelt Mecklenburg-Vorpommern, 1994.

MLR: Ministerium für ländliche Räume, Landesplanung, Landwirtschaft und Tourismus des Landes Schleswig-Holstein. Generalplan Küstenschutz – Integriertes Küstenschutzmanagement in Schleswig-Holstein, 2001.

NLWKN: Generalplan Küstenschutz Niedersachsen/Bremen – Festland. Küstenschutz Band 1. Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, 2007.

OUMERACI, H.: Küsteningenieurwesen. In: LECHER, K.; LÜHR, H.-P.; ZANKE, U. (eds.): Taschenbuch der Wasserwirtschaft, Berlin, Germany: Paul Parey Verlag, Kapitel 12, S. 657–743, 2001.

PETERS, K.; DAEMRICH, K.-F.; STOSCHEK, O. u. SCHÜTTRUMPF, H.: Arbeitsgruppe A5 – Küsten- und Seeseitiger Hochwasserschutz. Hansa International Maritime Journal (in print), 2008.

PULLEN, T.; ALLSOP, N. W. H.; BRUCE, T.; KORTENHAUS, A.; SCHÜTTRUMPF, H. and VAN DER MEER, J.W.: EurOtop – Wave Overtopping of Sea Defences and Related Structures: Assessment Manual. www.overtopping-manual.com, 2007.

SCHÜTTRUMPF, H.: Wellenüberlaufströmung bei Seedeichen – Experimentelle und Theoretische Untersuchungen (Wave Overtopping Flow at Sea Dikes – Experimental and Theoretical Investigations), http://www.biblio.tu-bs.de/ediss/data/20010703a/20010703a.html, PHD-Thesis, 2001.

SCHÜTTRUMPF, H. and OUMERACI, H.: Schäden an See- und Stromdeichen (Dike Failures at Sea and Estuary Dikes). Mitteilungen des Leichtweiss-Instituts für Wasserbau, H. 149, pp. 129–172, 2002.

SCHÜTTRUMPF, H.; OUMERACI, H.: Learning from Sea Dike Failures. PIANC-Bulletin N° 117, S. 47–60, 2004.

TAUTENHAIN, E.: Der Wellenüberlauf an Seedeichen unter Berücksichtigung des Wellenauflaufs. Mitt. des Franzius-Instituts, H. 53, S. 1–245, 1981.

WOEBCKEN, C.: Deiche und Sturmfluten an der Deutschen Nordseeküste (Dikes and Storm Surges at the German North Sea Coast). 1. Auflage. Friesen-Verlag Bremen-Wilhelmshaven, 1924.