Die Küste, 81 (2014), 491-501

Integrated Design of Sea- and Estuarine Dikes

Cordula Berkenbrink and Hanz Dieter Niemeyer

Summary

The impact of the expected changes in the global climate will create an unknown challenge for coastal protection. The anticipated acceleration of the sea level rise in combination with an expected higher set-up of storm surges will create higher storm surge levels and stronger waves. Existing guidelines for the design of dike heights only consider hydrodynamic loads, whereas the resistance of the dike body or the dike covering has not been part of the design criteria up so far. Therefore, dikes had to be heightened according to the hydrodynamic loads. To achieve an economical and safe design, it is necessary to consider the hydrodynamic loads in more detail, together with the soil mechanic resistance of the dike material. That was the idea behind the integrated design concept developed in the project "Integrated Design of Sea- and Estuarine Dikes" of the German Coastal Engineering Research Council (KFKI), funded by the German Federal Ministry of Education and Research (BMBF). To establish the quantification of the soil mechanic characteristics, a detailed knowledge of the hydrodynamic loads is essential. This cannot be adequately achieved by way of empirical relationships. In order to match such requirements, the mathematical model OTT-1d of HR-Wallingford was developed, validated, calibrated and verified. Implementing the model for design practice, it was extended in such a way, that different roughness sections can be considered and the loads of the inner slope can be quantified. Finally, the integrated design concept is shown for one typical type of dike, for varying load scenarios at the coast and in an estuary of Lower Saxony, respectively.

Keywords

integrated design, hydrodynamic loads, wave overtopping, climate change, overtopping security

Zusammenfassung

Der Klimawandel und seine Folgewirkungen werden den Insel- und Küstenschutz vor erhebliche Herausforderungen stellen, da von stark wachsenden Beanspruchungen der Schutzwerke auszugehen ist. Beschleunigter Meeresspiegelanstieg, wachsender Stau von Sturmfluten bewirken einerseits höhere Bemessungswasserstände und andererseits höhere Wassertiefen, die wegen der Tiefenbegrenzung des Seegangs vor den Schutzwerken dessen Zunahme ermöglichen. Insofern ist von einem erheblichen Wachsen, der in den gängigen Bemessungsansätzen berücksichtigten hydrodynamischen Belastungen, auszugehen. Sie bestimmen bei der gegenwärtigen Bemessungspraxis allein die Dimensionierung von Deichen.

Im Sinne einer effektiveren Bemessung von See- und Ästuardeichen hinsichtlich Sicherheit und Wirtschaftlichkeit erscheint deshalb eine differenziertere Berücksichtigung der hydrodynamischen Belastungen in Verbindung mit der berücksichtigten bodenmechanischen Widerstandsfähigkeit der beim Deich verwendeten Erdbaustoffe unverzichtbar. Um diese Zielsetzung zu erreichen wurde ein entsprechendes Konzept für das Forschungsvorhaben „Integrierte Bemessung von See- und Ästuardeichen" entwickelt, das *vom Kuratorium für Forschung im Küsteningenieurwesen (KFKI) gebilligt und vom Bundesministerium für Bildung und Forschung (BMBF) gefördert wurde.*

Die Umsetzung des Forschungsvorhabens erfolgte einerseits durch eine Identifikation geeigneter bodenmechanischer Parameter zur Charakterisierung der Widerstandsfähigkeit der verwendeten Erdbaustoffe gegenüber den erfolgenden hydrodynamischen Belastungen. Sie wurden andererseits wesentlich differenzierter analysiert als mit den gegenwärtig genutzten empirischen Bemessungsansätzen möglich, um ein integriertes hydrodynamisch-bodenmechanisches Bemessungsverfahren entwickeln zu können. Hierfür wurde das bei HR Wallingford entwickelte mathematische Wellenauf- und -überlaufmodell OTT-1D genutzt. Es wurde verifiziert, kalibriert und für die Anwendung in der Bemessungspraxis dahingehend tauglich gemacht und optimiert, dass die hydrodynamischen Belastungen der Innenböschungen quantifiziert werden können und Baukörperabschnitte mit unterschiedlichen Rauhigkeitsabschnitten berücksichtigt werden können. Im Anschluss wird das neuentwickelte integrierte hydrodynamisch-bodenmechanische Bemessungskonzept repräsentativ auf einen exponierten Seedeich und einen Ästuardeich in Niedersachsen angewendet. Mit Hilfe des differenzierten Bemessungsansatzes werden für diese Deiche die Potenziale an Belastungsreserven aufgezeigt, die sich bei seiner konsequenten Anwendung in Zukunft nutzen werden lassen, um einen Teil der aus Klimaänderungsfolgen herrührenden zusätzlichen Belastungen ohne weitere Erhöhungen von Deichen kompensieren zu können.

Schlagwörter

Insel- und Küstenschutz, integrierte Bemessung, Erdbaustoffe, Hydrodynamik, Bodenmechanik, Wellenüberlauf, Überlaufsicherheit, Klimaänderungsfolgen

Contents

1 Introduction and Motivation

Wave Overtopping is an important design criterion for coastal structures; in the past it has been the most common indicator for dike failure on the German coast. Knowing this, it is important to obtain reliable data for this hydrodynamic load in order to improve the safety of coastal structures against the background of rising sea levels and increased storm intensity. At present, the prediction of overtopping discharge is calculated by empirical formulae, which are limited to definite structures and wave conditions. They are determined through hydraulic tests for defined wave and structure parameters. For geometries or wave conditions not examined in these hydraulic tests, these methods are not always reliable and lead to both over- and underestimations. Mathematical models are able to simulate wave overtopping more precisely than empirical relationships can, because the detailed geometry of the structure and the whole spectrum of the wave field can be considered and easily changed.

Project partners from the Institute of Soil Mechanics and Foundation Engineering of the University of Duisburg-Essen analysed the soil mechanical processes for a functional optimization of dike elements. An example is given to show the integration of the hydrodynamic loads and the soil mechanical resistance for an integrated design concept for dikes.

In situ investigations of dike overtopping security in the Netherlands documented that a dike could withstand overtopping rates up to 50 l/(m·s) without damage (Fig. 1) (VAN DER MEER et al. 2009). Therefore, in countries with lowlands like Germany or the Netherlands, ambitious research programs are carried out in order to intensify and increase the knowledge on wave overtopping security of dikes.

Figure 1: Inner slope of a dike in Delftzijl during in situ overtopping tests.

Aim of the project is to quantify the resistance of a dike through a comparison of local hydrodynamic loads with specific resistance parameters of the soil. Mechanical characteristics of construction material will be considered, based on data from other engineering sectors. The necessary safety standard can be optimized by connecting loads and load capacity. Furthermore, safety deficits on existing dikes can be localized in order to deploy a priority concept.

2 Recent improvements in dike design in Lower Saxony, Germany

The determination of design wave run-up for dikes has been seriously taken into consideration following the disastrous storm surge of February 1962, which had a death toll of more than 300 people (LÜDERS and LEIS 1964). But the lack of information of the local wave climate in the morphologically enormously differentiated coastal areas and estuaries initially only allowed for an empirical design. This design was oriented along data about wave run-up which had occurred during storm surges in the past. In order to provide sufficient security for the hinterland, estimates of design wave run-up have been carried out by anticipating rather high values for long stretches as a whole (Fig. 2). Since 1976, measurements of flotsam benchmarks were not only used for the identification of wave run-up but also for its extrapolation for design conditions (NIEMEYER 1977), (NIEMEYER et al. 1995) allowing a more differentiated evaluation of design wave run-up (Fig. 2).

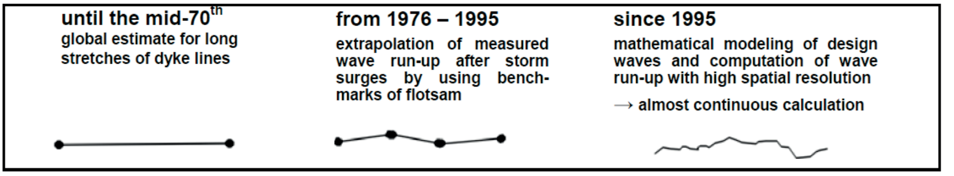

Figure 2: Changes in the evaluation of design wave run-up in Lower Saxony within the last decades (NIEMEYER et al. 2010).

Since 1997, design wave conditions are determined by applying the third generation full-spectral wave model SWAN (RIS, HOLTHUIJSEN and BOOIJ 1995) providing the input for modified wave run-up formulas (e.g. VAN GENT 1999) under consideration of an accepted overtopping rate of 3 % (NIEMEYER and KAISER 2001). Such detailed studies allow a much more differentiated determination of dike heights than before.

3 Integrated approach

3.1 Schematic representation

The research project "Integrated Design of Coastal and Estuarine Dikes" is aimed at the development of design procedures, under quantitative consideration of the detailed hydrodynamical loads, as well as the strength of the clay of dikes (Fig. 3).

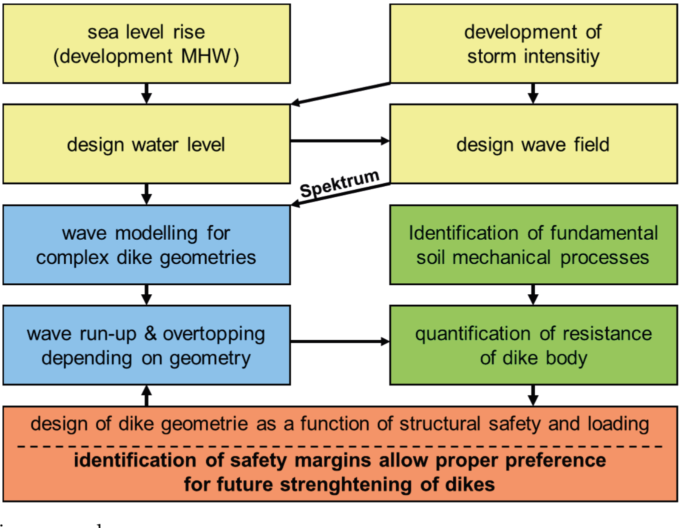

Figure 3: Design procedure.

For the evaluation of the design water level, as well as the design wave field, the design methods of the Federal State of Lower Saxony in Germany were used. Wave run-up, and wave overtopping respectively, were calculated in more detail using mathematical modelling instead of empirical relationships. This has the advantage that nearly every structure and every wave field can be taken into account. Furthermore, the hydrodynamic loads can be identified at every point of interest for the soil mechanical functions.

3.2 Description and modification of the mathematical model

The mathematical model applied here is called OTT-1d developed by HR Wallingford (DODD et al. 1998) and is part of the ANEMONE group (Advanced Non-linear Engineering Models for the Nearshore Environment). It is based on the nonlinear shallow water (NLSW) equations, which describe the horizontal mass and momentum balance. They are solved explicitly using the finite volume method. The advantage of the OTT-1d model, in contrast to other similar NLSW-Models, is the use of the Godunov-type scheme. Water volumes can be treated equally in each computational node; that allows for the calculation of separated water volumes. The regeneration of waves by overtopping volumes in lee of the structure can also be modeled. Wave breaking is implicitly included by building a bore. The numerical waves steepen and form shocks with a vertical face. OTT-1d has very robust numerical solvers and runs efficiently and stable. The input parameters are reduced to a minimum.

Some modifications were necessary to be able to use the model for complex or real scale structures (BERKENBRINK et al. 2009). In a first step, the input and output parameters and the model domain were increased. Further, the still water level at the inner slope was reprogrammed to make calculation of hydrodynamic loads at the inner slope possible. Finally, the modified model is able to build up different roughness sections in the model domain. Previously, the roughness factor was assumed to be constant over the entire dike, resulting in the inability to model complex revetments. The accuracy of all those modifications has been verified through the output signals at the crest.

4 Example for the integrated design

Numerous tests were carried out during the project, which cannot all be introduced in this paper. A typical dike profile on the East Frisian coast in Lower Saxony was chosen as a representative example. It has a crest height of about 8.0 m above NN, an outer slope of 1:6 and an inner one of 1:3. The clay layer has a thickness of 1.5 m at the outer slope and crest and of 1.0 m on the inner slope (Fig. 4).

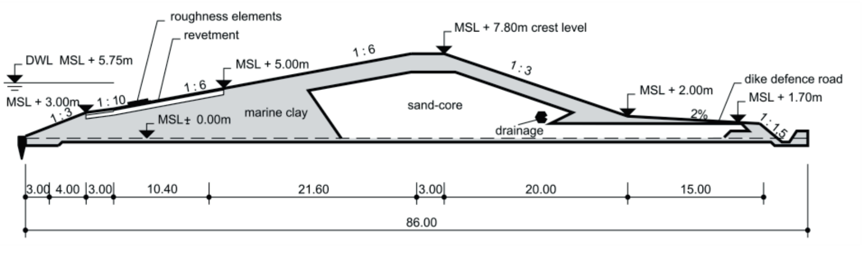

Figure 4: Dike profile at the East Frisian coast of Lower Saxony.

After creating a design procedure set-up, the dikes were tested in different scenarios of anticipated design water levels ranging from 5.0 m to 7.5 m above German Datum NN; with steps of 0.5 m. The present design water level is about 5.75 m above NN. For all these water levels between the the lowest and highest, design waves have been modeled by SWAN, (Fig. 5). The range of significant wave heights, energy periods and mean wave direction varies correspondingly as follows:

$$1.76 \text{ m} \leq H_{m0} \leq 2.48 \text{ m}$$
$$3.6 \text{ s} \leq T_{m-1,0} \leq 5.4 \text{ s}$$
$$310° \geq \theta_m \geq 303°$$

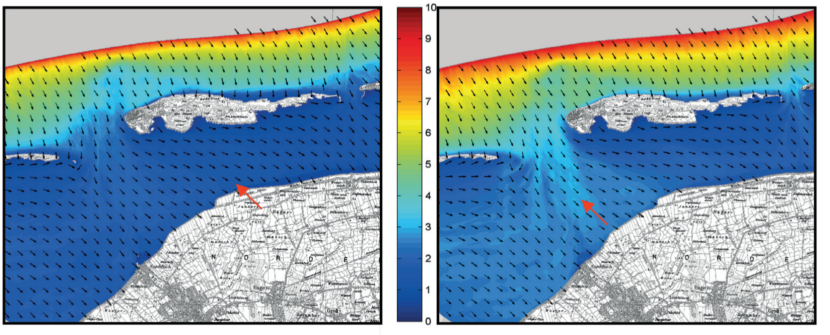

Figure 5: Significant Wave Heights [m] modeled by SWAN (left panel: supposed design water level: 5 m above German datum, right panel: anticipated design water level: 7.5 m above German datum) (BERKENBRINK et al. 2010).

The wave spectra at the toe of the dike at an exposed position for each anticipated design water level are used as boundary conditions for modelling wave run-up and overtopping on the dike (modelling was carried out by OTT-1d model).

The mean overtopping rates increase enormously with rising design water levels and wave parameters (Fig. 6), reaching a maximum of approximately 200 l/(s·m) for a design water level of NN+ 7.5 m. The present design water level leads to low mean overtopping rates. For higher overtopping rates, the tolerable design water level could be raised (see the tests in Delfzijl). The dike was able to bear 50 l/(s·m), amounting to a tolerable design water level of NN +6.7 m for this example. These mean overtopping rates, their corresponding layer thicknesses and velocities have been used in order to determine the capacity of a distinct clay quality.

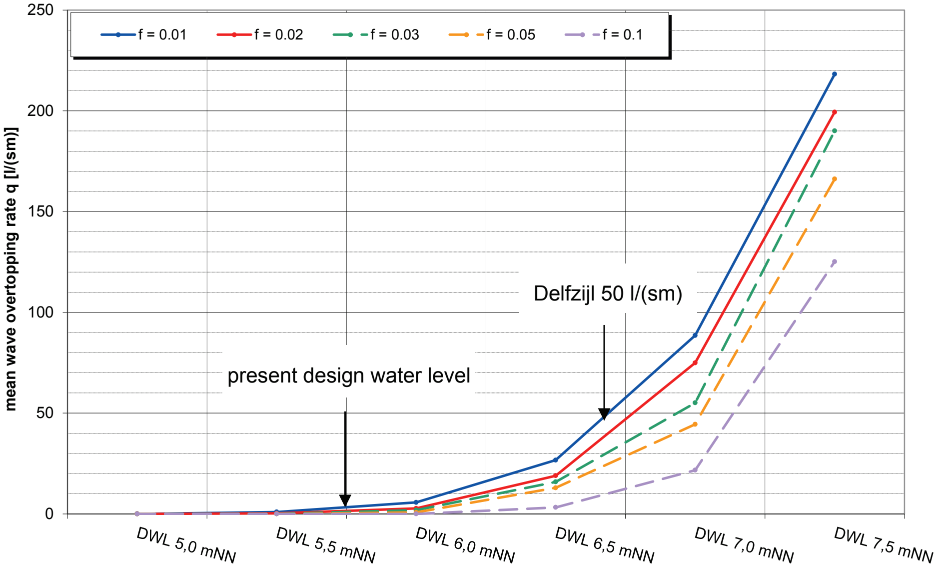

Figure 6: Mean Overtopping rates for different design level scenarios and roughness factors.

The hydrodynamic loads result in soil mechanical processes like erosion and infiltration. Because of this consistent wetting, the soil softens and loses its strength. The Inner slope is saturated with overtopping water and, in combination with the soil dead weight, the flow forces can initiate slope parallel sliding of the cover layer (Fig. 7). The sand-core is then defenseless against the following overtopping waves. Usually, the slope parallel sliding is signalized by fissures along the dike crest and a bulge at the inner toe (WEIßMANN 2003).

Figure 7: Slope parallel sliding.

With the hydrodynamic loads modeled by OTT-1d, the level of utilization for slope parallel sliding is calculated for different types of soil. They are categorized by WEIßMANN (2003), ranging from "less qualified" (Elisabethgroden 3.5) over "well qualified" (Elisabethgroden 9.0, Wustrow) up to "very well qualified" (Cäciliengroden I, II, Hohenkirchen (Fig. 8). Every type, except "Wustrow", is clay. "Wustrow" is a marly soil. The safety against slope parallel sliding is given by the level of utilization $\alpha_s < 1$.

The "less qualified" soil is above that level, whereas the higher qualified soil is not. The resistance of the soil increases further with the grade of compression (Fig. 8).

The higher grade of compression results in a lower level of utilization, as there are less cavities and a lower level of saturation.

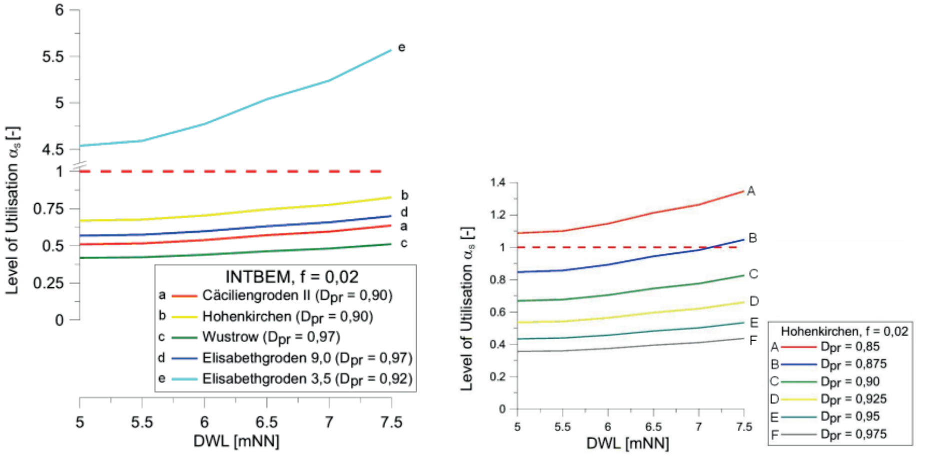

Figure 8: Safety against slope parallel sliding for different types of soil (RICHWIEN et al. 2010).

5 Potential for Compensation of Future Climate Change Impacts

The results of the research project highlight the fact that the clay covers of numerous dikes are capable of withstanding higher overtopping rates than presently assumed for their design levels. In order to quantify this enormous potential, the effect on the increase of an acceptable design water level in dependence of the overtopping tolerance is documented for both an exposed coastal and an estuarine dike (Fig. 9 and 10).

For the investigated exposed coastal dike, an increase of the design water level of more than 50 cm would be acceptable for a tolerable overtopping rate of 10 l/(m·s) and of nearly 70 cm for a tolerable overtopping rate of 15 l/(m·s) (Fig. 9) without requiring any strengthening of the structure. These values are not only based on the tests with the applied mathematical models; they are still remarkably lower than maximum values of the site tests in Delfzijl, during which no damage to the dike took place.

A similar result was achieved through the model tests for an estuarine dike with smaller wave attack (Fig. 10): An assumed tolerable overtopping rate of 10 l/(m·s) would allow an increase of the design water level of more than 50 cm and of more than 60 cm for an overtopping rate of 15 l/(m·s).

These examples highlight the benefits which are achievable through the application of an integrated design of coastal and estuarine dikes. Prerequisite for a reliable integrated design will be sufficient information about the relevant soil parameters of the clay covers implemented in the dikes. In relation to the expected cost of strengthening such structures, the benefits of a campaign to evaluate the soil parameters required for an integrated design are expected to be very high.

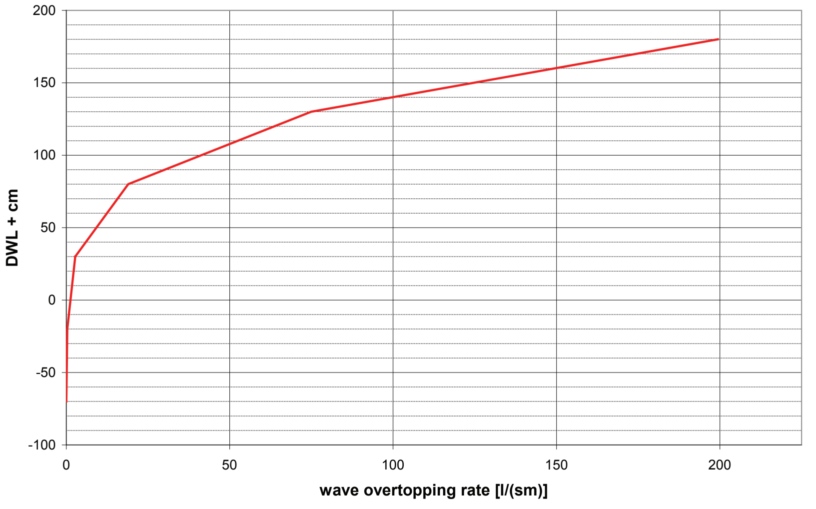

Figure 9: Cumulation of acceptable design water level increase in dependence of overtopping tolerance for an exposed coastal dike (NIEMEYER et al. 2010).

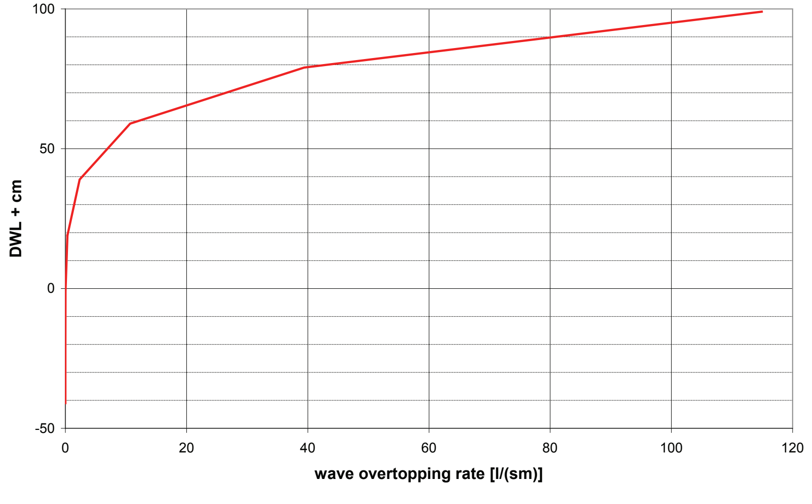

Figure 10: Cumulation of acceptable design water level increase in dependence of overtopping tolerance for an estuarine dike (NIEMEYER et al. 2010).

6 Summary and Conclusions

Aim of the project was the development of a new design concept for coastal and estuarine dikes. In addition to hydrodynamic loads, the detailed bathymetry in front of the dike and the quality of the implemented soil material will be considered quantitatively for the design. Thus, dikes can be dimensioned with improved safety and in a more economical way. Safety reserves or safety deficits of existing dikes can be detected and quantified in order to highlight priorities for necessary reinforcements.

For the evaluation of the hydrodynamic loads, the mathematical model OTT-1d by HR Wallingford has been modified with respect to large scale conditions. The model considers the detailed geometry which allows the calculation of layer thickness, flow velocity, wave run-up and wave overtopping at every position of the structure. The hydrodynamic loads result in soil mechanical processes like erosion and infiltration. Because of this consistent wetting, the soil softens and its strength is reduced. The Inner slope is saturated with overtopping water and, in combination with the soil dead weight, the flow forces can initiate slope parallel sliding of the cover layer, which leaves the sand-core defenceless against the following overtopping waves. The overall resistance of the dike body is given by the level of utilisation for the loading cases for different types of soil.

There is an enormous potential for additional safety of coastal and estuarine dikes with respect to acceptable overtopping rates. The currently applied design procedures with their very conservative low overtopping tolerances require higher dikes than necessary. The research of the project should be intensified in the near future in order to establish new design procedures. Future results could lead to immediate and cost-saving countermeasures to counteract the effects of the accelerating rise in sea-levels.

7 Acknowledgements

The work presented here is part of the research project "Integrated Design of Sea- and Estuarine Dikes" (INTBEM) within the framework of the programme of the German Coastal Engineering Research Council (KFKI) and funded by the German Federal Ministry of Education and Research (BMBF) – project code: 03 KIS 061/062. We would like to thank our project partners Werner Richwien, Carsten Pohl and Lars Vavrina of the Institute of Soil Mechanics and Foundation Engineering of the University of Duisburg-Essen, and our colleagues from the Coastal Research Station (NLWKN), Ralf Kaiser and Markus Witting, for their support, inspiration and cooperation.

8 References

BERKENBRINK, C.; KAISER, R. and NIEMEYER, H.D.: Prototype Overtopping Measurements and Model Verification. In: Proc. 31st Int. Conf. o. Coast. Eng. MC KEE SMITH, J. (Ed.), Bd. 4, Hamburg, 3009-3019, 2009.

BERKENBRINK, C.; KAISER, R. and NIEMEYER, H.D.: Mathematische Modellierung hydrodynamischer Bealastungen von Deichen. Die Küste, Heft 77, KFKI (Ed.), Boyens & Co. KG, Heide i. Holstein, 2010.

DODD, N.; GIARRUSSO, C.C. and NAKAMURA, S.: ANEMONE: OTT-1d – A User Manual. Report TR 50 - HR Wallingford, 1998.

LÜDERS, K. and LEIS, G.: Niedersächsisches Deichgesetz – Kommentar. In: Wasser und Boden, Hamburg, 1964.

NIEMEYER, H.D.: The Estimation of Design Wave Run-up on Sea Dykes in Consideration of Overtopping Security. Proc. 17th IAHR-Congress, Baden-Baden, 1977.

NIEMEYER, H.D.; GÄRTNER, J.; KAISER, R.; PETERS, K.-H. and SCHNEIDER, O.: Estimation of Design Wave Run-up on Sea Dykes under Consideration of Overtopping

Security by Using Benchmarks of Flotsam. In: Proc. 4th Conf. Coast. & Port Eng. i. Develop. Countr., Rio de Janeiro/Brazil, 1995.

NIEMEYER, H.D. and KAISER, R.: Design Wave Evaluation for Coastal Protection Structures in the Wadden Sea. In: Proc. 4th Int. Symp. Ocean Wave Meas. & Analysis 2001. San Francisco. ASCE, Reston/Va., USA, 2001.

NIEMEYER, H.D.; KAISER, R. and BERKENBRINK, C.: Increased Overtopping Security: A Potential for Compensating Future Impacts of Climate Change. In: Proc. 32nd Int. Conf. Coast. Eng. Shanghai/China 2010 (www.journals.tdl.org/icce/index.php /icce/issue/view/154/showToc).

RICHWIEN, W.; POHL, C. and VAVRINA, L.: Bemessung von Deichen gegen Einwirkungen aus Sturmfluten. Die Küste, Heft 77, KFKI (Ed.), Boyens & Co. KG, Heide i. Holstein, 2010.

RIS, R.; HOLTHUIJSEN, L.H. and BOOIJ, N.: A Spectral Model for Water Waves in the Nearshore Zone. In: Proc. 24th Int. Conf. Coast. Eng. Kobe/Japan. ASCE, New York, 1995.

VAN GENT, M.: Wave run-up and Overtopping for Double Peaked Wave Energy Spectra. WL|Delft Hydraulics Report H 3351, 1999.

VAN DER MEER, J.W.; STEENDAM, G.J.; DE RAAT, G. and BERNARDINI, P.: Further Developements on the Wave Overtopping Simulator. In: Proc. 31st Int. Conf. o. Coast. Eng., MCKEE SMITH, J. (Ed.). Bd. 4. Hamburg, 2957–2696, 2009.

WEIßMANN, R.: Die Widerstandsfähigkeit von Seedeichbinnenböschungen gegenüber ablaufendem Wasser, Universität Duisburg-Essen, In: Mitteilungen aus dem Fachgebiet für Grundbau und Bodenmechanik, Heft 30, Glückauf Verlag, Essen, 2003.