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HYDRAULIC INFLUENCE OF NAVIGATION CHANNELS ON FLOOD DEFENCE STRUCTURES

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ABSTRACT

Ship induced processes were made responsible by the local authorities for dike and revetment failures in the outer part of the Elbe estuary. The German Federal Waterways Administration, responsible for the maintenance of the navigation fairway, commissioned the Federal Waterways Engineering and Research Institute (BAW) to investigate the ship-induced processes by field measurements and to explain the observed failures. It can be shown that ship induced processes such as ship induced pore pressure variations in the dike and the subsoil as well as vibrations caused by ships do not influence the stability of the dike. Nevertheless, the revetment failures can be partly explained by the effect of ship waves but also by wind waves.

SOMMAIRE

L'effet de navires a été fait responsable par les autorités locales pour les dommages de digues et d'enrochements dans l'estuaire de l'Elbe en Allemagne. L'institut fédéral d'études et de recherches des voies navigables (BAW) a été chargé par l'Administration Fédérale allemande des Eaux et de la Navigation (WSV) d'étudier l'effet de navires et d'expliquer les dommages observées. Les mesures en nature ont prouvé que l'effet de navires ne cause pas les dommages de digues observées mais peuvent être une raison pour les dommages d'enrochement.

KEYWORDS
Dike, revetment, estuary, fairway, ship waves, wind waves, safety, field measurements, pore pressures, vibrations

1. INTRODUCTION

Failures of dikes, revetments, groins and other structures in estuaries and at the coast are caused mainly by water level variations, currents, wind waves and ship waves. Therefore, the notion of the interactions of the hydraulic stresses and the geotechnical resistance is relevant for the design of these kind of structures. Objective of the present study was to investigate the dynamic interactions between ship induced hydraulic stresses and the geotechnical processes based on field measurements. Ship-induced stresses of estuarine structures in the vicinity of maritime fairways play an important role with respect to previous and future adjustments of the fairway dimensions due to the increasing size of large container ships (Figure 1) but also with respect to the maintenance of the fairways. The present study is focusing on ship induced stresses of estuarine dikes. Estuarine dikes protect the low-lying hinterland during high storm surges. Thus, estuarine dikes are designed to withstand high water levels and wave conditions. The influence of ship-induced stresses on estuarine dikes was never investigated since the effect was assumed to be negligible and storm conditions are more relevant for estuarine dikes.

Figure 1: Large container vessel in front of the dike

The motivation for the present case study arises from failures of dikes and revetments in the outer part of the Elbe estuary in Germany (Figure 2). Ship induced stresses and the last fairway adaptation were made responsible for these failures by the local authorities of the dike. Therefore, the Federal Waterways Engineering and Research

Institute (BAW) was commissioned by the German Federal Waterways Administration (WSV) to investigate the influence of ship induced stresses on estuarine dikes. A general investigation was required with respect to a new adjustment of the Elbe fairway which is in its planning phase. A typical cross section of a dike profile in the Elbe estuary is given in Figure 3.

The paper will give an overview of the field investigations performed in the Elbe estuary. First, a general description of the generation of ship waves and their influence on the dike, the revetment and the foreshore is given. Then, the set-up of the field measurements is described shortly. Afterwards, results are presented on ship-induced vibrations of the dike, ship-induced pore pressure variations in the dike and the subsoil and on the influence of ship waves on the stability of the revetment. Conclusions concerning the influence of ship waves on the dike are given at the end of the paper.

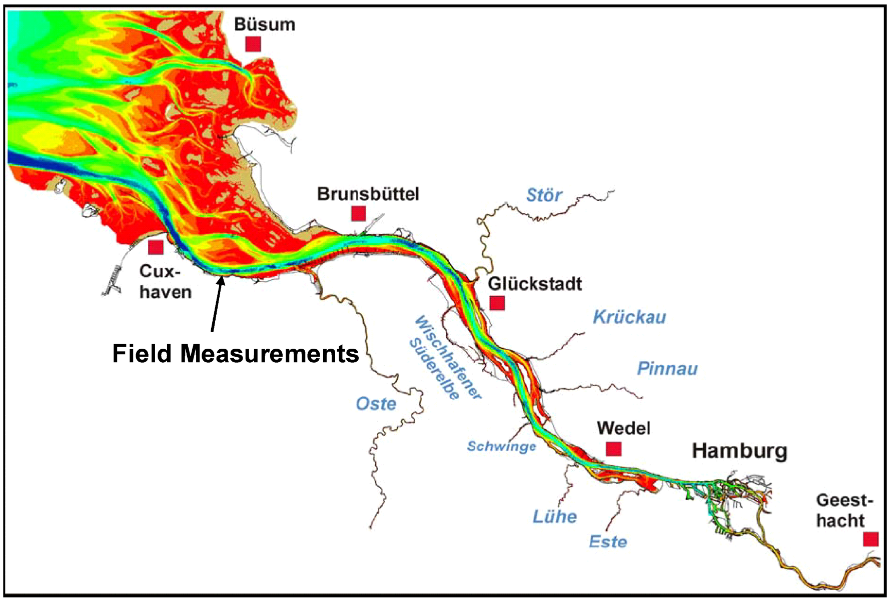


Figure 2. Elbe estuary and field site for in-situ measurements

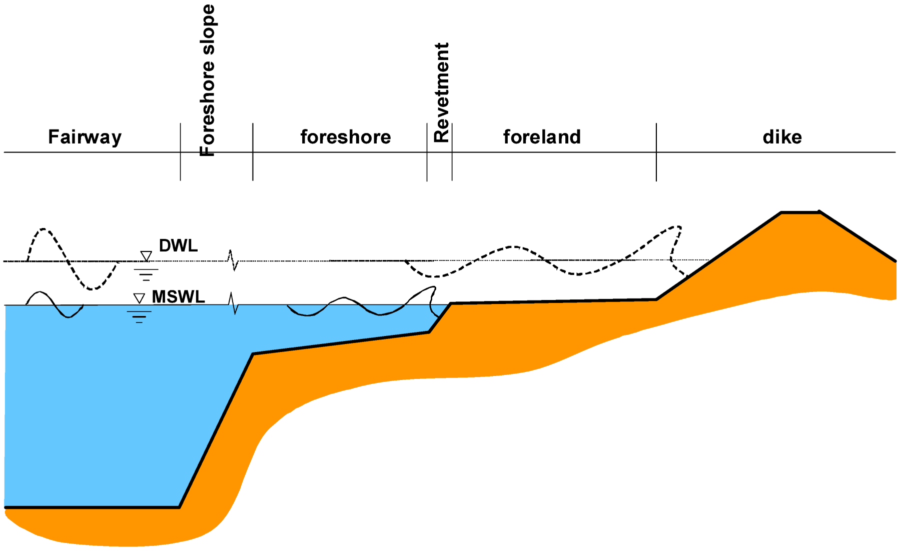
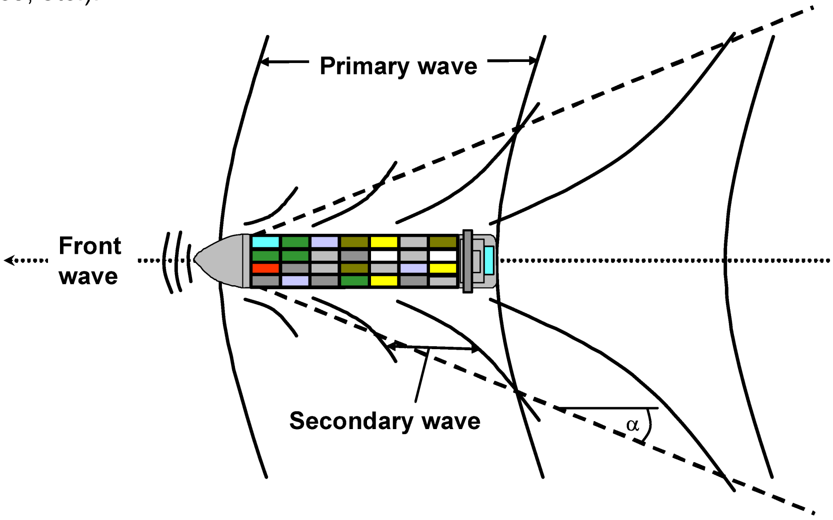


Figure 3. Typical cross section of a dike in the Elbe estuary

2. SHIP WAVES – GENERAL DESCRIPTION

The sailing ship transfers energy to the water body in order to overcome the resistance of the ship by inducing a return current. Because of the conservation law of energy, a water level variation along the ship hull can be associated to the local return current. This causes a front wave at the bow of the ship, a drawdown wave along the ship and a stern wave. Bow wave, drawdown wave and stern wave cause a wave system which is called primary wave system. The primary wave system propagates in the direction of the sailing ship.

In addition, secondary waves are generated because of different pressures terms along the ship which propagate under an oblique angle to the sailing line of the ship. Both, the primary and the secondary wave system are illustrated for deep water wave conditions in Figure 4. Primary wave and secondary waves generate a constant wave pattern with cusps formed on a line with an angle of 19°28’ to the sailing line of the ship in deep water. These wave patterns were first investigated by Lord Kelvin in 1887. Attempts were made among others by Lord Kelvin (1887) and Havelock (1908) analytically, by Johnson (1957), Sorensen (1973), Sorensen and Weggel (1984) and Kriebel and Seelig (2005) experimentally and by Doorn et al. (2002), JIANG et al. (2002), MacDonald (2003), Nwogu (2004) numerically to describe the generation and the propagation of ship waves. Despite the progress made by the aforementioned investigations, field measurements are required to obtain the ship wave climate for complex topographic and hydrodynamic boundary conditions and complex ship movements (different types, speed, draught, sailing distance, etc.).



α=19,28° (Kelvin angle)

Figure 4: Generation of ship waves in deep water

An observer at any point between the ship and the shore notices a wave system as illustrated in Figure 5:

- Front wave s_B
- Drawdown or water level depression z_A
- Primary wave height H_p
- Secondary wave height H_{sec}
- Period of the primary wave T_{Hp}
- Period of the secondary wave T_{Hsec}

These parameters depend on the characteristics of the ship (speed, length, width, draught, etc.), the geometry of the waterway (cross section, water level, tidal currents, etc.) and other physical parameters.

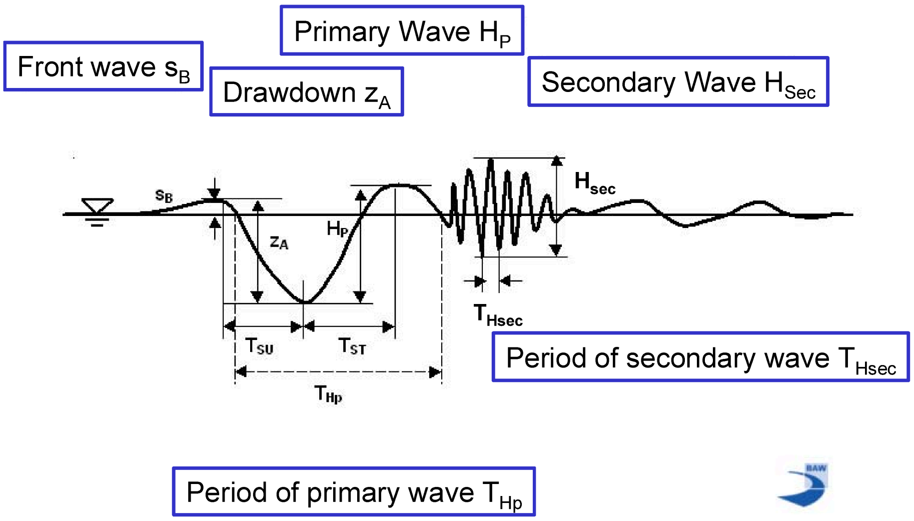


Figure 5. Definitions of ship waves.

The celerity of the primary wave system is higher than the celerity of the secondary waves due to the wave period of the primary wave system in the order of minutes. The wave celerity can be calculated by the shallow water wave celerity $c=(g\cdot d)^{1/2}$ depending on the local water depth d. The primary wave system is transformed by the underwater topography and by the shallow water effects (shoaling, refraction, diffraction, wave breaking) in size and direction from the fairway to the revetment. At the revetment, the primary wave systems induces first a water level set-up (bow wave), a water level depression (drawdown) and a second water level set-up (stern wave). A hydraulic gradient is induced in the subsoil of the revetment by the water level depression which is directed seawards.

The secondary waves arrive after the primary wave system at the revetment. The wave periods of the secondary waves are in the order of 3 to 5 seconds (Figure 6). Secondary waves are transformed by the underwater topography and behave like short periodic wind waves. Secondary waves often break on the foreshore or at the revetment depending on the local water depth.

The knowledge of ship waves is required because they can have a significant hydrodynamic impact on berthed vessels, on estuarine structures, on coastal erosion and even on the safety of people on the beach. In the context of this study, only the influence of ship waves on estuarine structures such as dikes and revetments is of interest.

Ship induced effects on the estuarine dike, the revetment and the foreshore are presented in Figure 7. The effects on the dike can be subdivided in ship induced pore pressure variations and ship induced vibrations and the effect on the stability and the deformation of the dike. The stability of the revetment was also investigated.

Other ship impacts on estuarine structures such as ship collisions are not subject of this study (Kramer et al., 2006).

Figure 6. Secondary waves

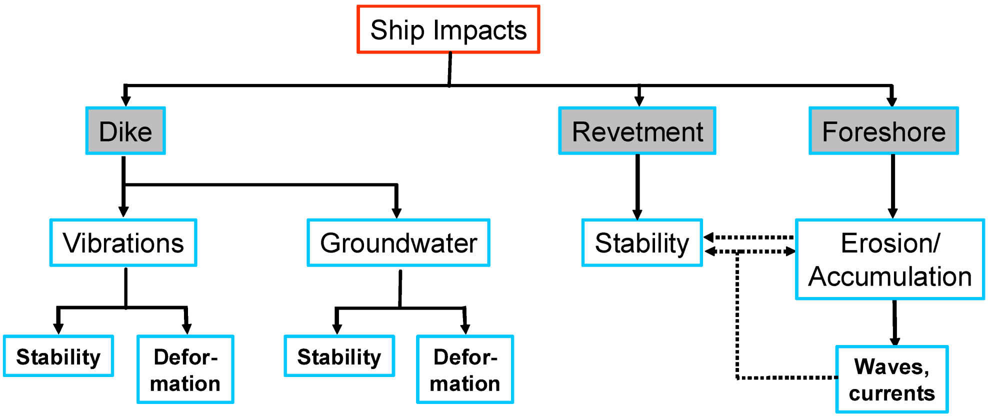


Figure 7: Ship induced effects on the dike, the revetment and the foreshore

3. SET-UP OF FIELD MEASUREMENTS

Measurement devices were installed seawards and landwards of the water line to investigate the influence of ship induced waves on the geotechnical behaviour of the dike. Instruments to measure tidal water level variations, wind waves, ship waves, currents and turbidity were installed at two positions on the foreshore (LZ3 and LZ3a in Figure 8) in a distance of 75 m and 150 m to the revetment. Pore pressure variations were measured at in total 15 positions by applying pressure sensors which were vertically distributed in the different groundwater layers and in the core of the dike (Figure 12) at the positions PWD_1 to PWD_6 (Figure 8). (Remark: Notation of pressure cells:

PWD_X_Y with: X = horizontal position (see Figure 8) and Y = vertical position (1 = core; 2 = upper sand layer; 3 = lower sand layer)). All signals were recorded with a sampling rate of 20 Hz. The measurement devices were on site for three months from August to November 2005. In total, a number of more than 11500 ships were recorded during the measuring interval for moderate tidal conditions (no exceptional storm surges). All signals were measured automatically.

Vibrations were measured at four positions corresponding to the positions PWD_1 to PWD_4 near the surface of the dike using geophones and acceleration meters. A sampling rate of 315 Hz was chosen for vibration measurements. The field measurements for vibrations were performed in April 2005. Since it is difficult to distinguish between ship induced vibrations and other sources, the signals were recorded only during the passage of a ship.

In order to associate ship induced variations of the water level, the pore pressure and the ship itself, an AIS-system (Universal Shipborne Automatic Identification System) was installed to record data such as type of ship, length and width of ship, draught of ship, ship speed and sailing distance to the dike.

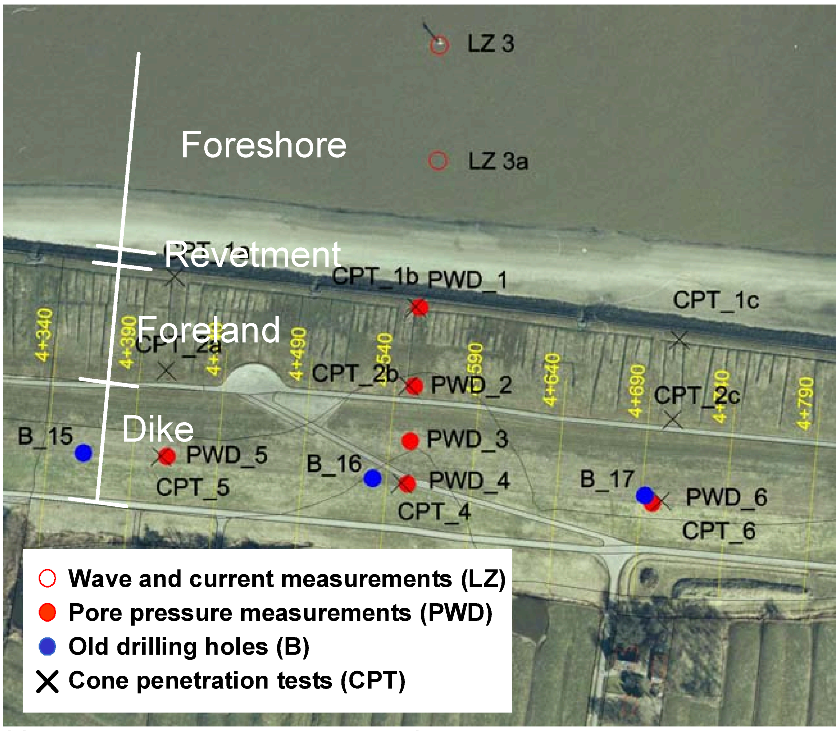


Figure 8. Set-up of field measurements – Positions of measurement devices in the dike, on the foreland, in the revetment and on the foreshore

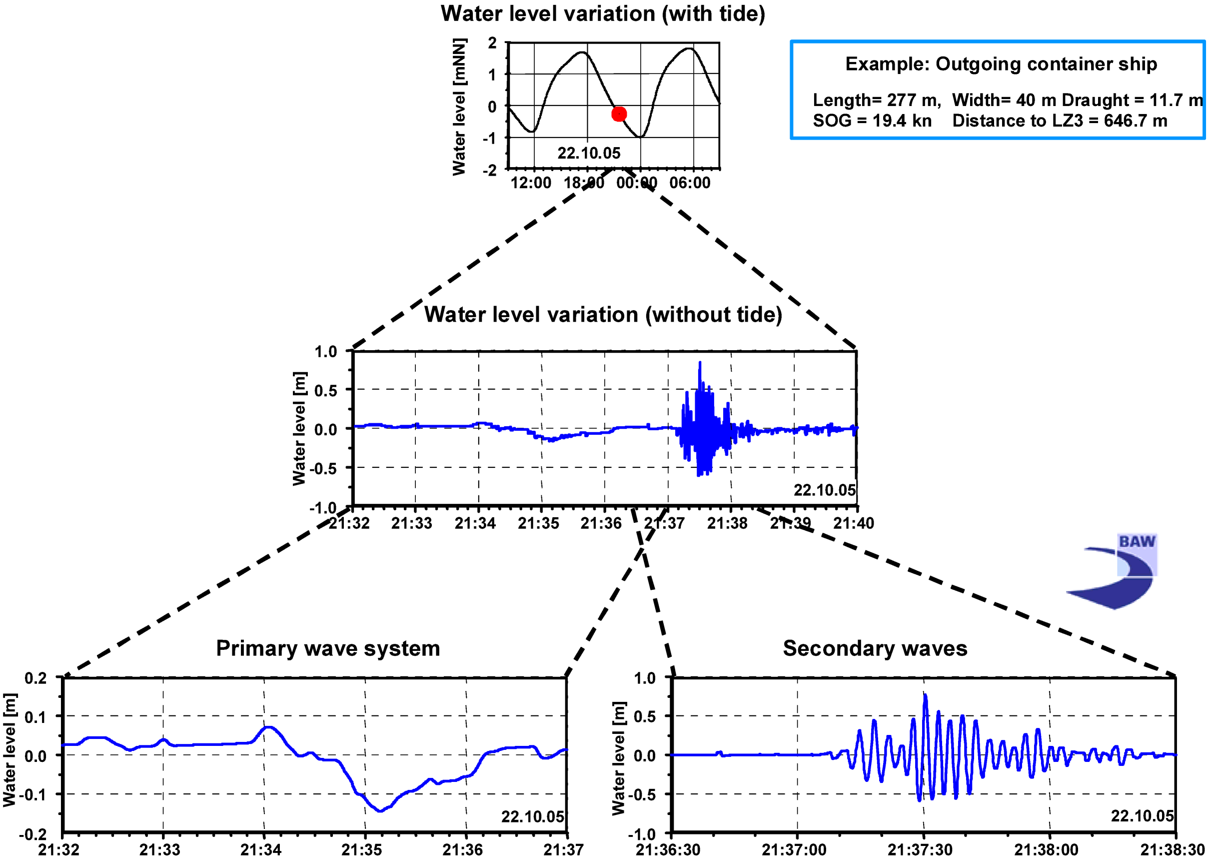
4. SHIP WAVES

An example of the data analysis for ship waves is given in Figure 9. The tidal signal was subtracted. Then, a distinction was made in primary waves and secondary waves by using different filter techniques. The maximum daily event was used for further statistical analysis. The following maximum values were measured during the field measurements:

- Maximum drawdown: $z_A = -0.49$ m
- Maximum primary wave height: $H_P = 0.52$ m
- Maximum secondary wave height: $H_{sec} = 1.43$ m (see Figure 9)
- Wave period of maximum secondary wave height: $T_{Hsec} = 3.0$ s

The maximum significant wave height (wind induced) was $H_S = 1.02$ m with a mean wave period of $T_m = 4.7$s. It has to be mentioned that the maximum secondary wave height corresponds to one single measured wave height while the significant wave height is a representative wave height for a wave train (either obtained by frequency or time domain analysis) which is not identical to the maximum wave height.

All data were used for further statistical analysis by fitting statistical distribution functions. Thus, the data were prepared for probabilistic analysis.



Example: Outgoing container ship

Length= 277 m, Width= 40 m Draught = 11.7 m
SOG = 19.4 kn Distance to LZ3 = 646.7 m

Primary wave system
Bow wave 0.07 m
Stern wave 0,02 m
drawdown 0.22 m
Primary wave 0.17 m; T_{Hp} = 90 s

Secondary waves
Wave height H_{sec} = 1.43 m
Wave period T_{Hsec} = 3.0 s

Figure 9. Analysis of ship waves (Example)

5. VIBRATIONS OF THE DIKE

Ship induced vibrations were made responsible for the observed dike failures amongst other loads. Therefore, vibrations were measured at four positions in the profile of the dike to investigate the influence of ships on the stability of the dike and on the particle redistribution. Ship induced vibrations of the dike can be caused in two different ways. On one hand, vibrations are transferred from the ship hull to the water body and from the water body to the subsoil of the dike. These vibrations can be measured during the passage of a ship. On the other hand, secondary ship waves cause vibrations of the dike when they arrive at the revetment and break. Vibrations induced by secondary ship waves can be observed a few minutes later than vibrations caused by the ship passage depending on the sailing distance of the ship to the dike. A typical example of the recorded vibration velocity caused by secondary ship waves is given in Figure 10. The vibration velocity is decreasing significantly from the revetment to the dike. Anyway, the amplitude of the observed vibration velocities caused by ships is small compared to other sources of vibration (Figure 11) and far below having an effect on the stability of the dike or the particle redistribution.

Ships were advised to sail at maximum possible ship speed during the vibration measurements. Therefore, it can be concluded that ship-induced vibrations have no significant effect on the stability of the dike or on the particle redistribution and so vibrations caused by ships are not responsible for the observed failures of the dike.

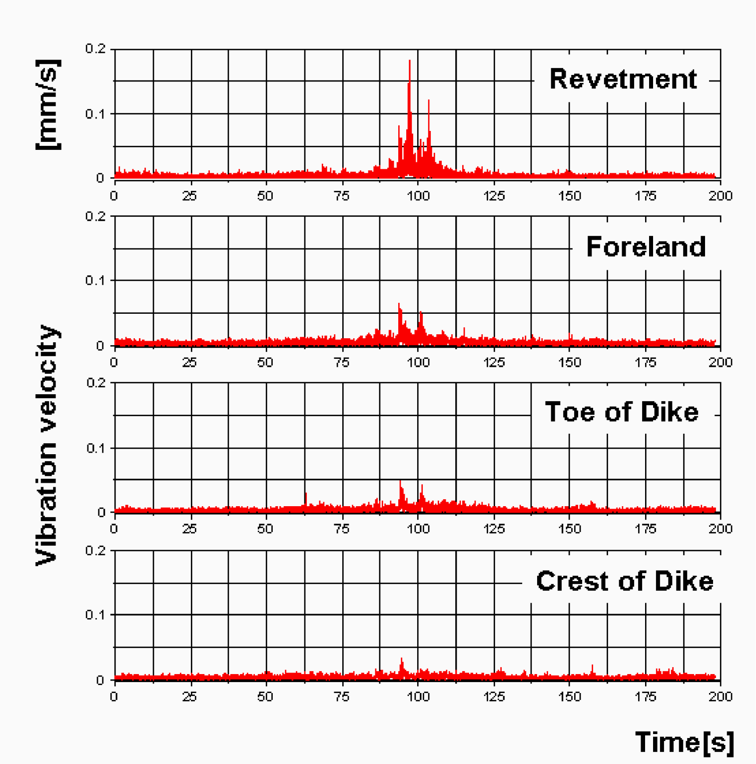


Figure 10. Evolution of vibration velocity from the revetment to the crest of the dike (example caused by secondary ship waves)

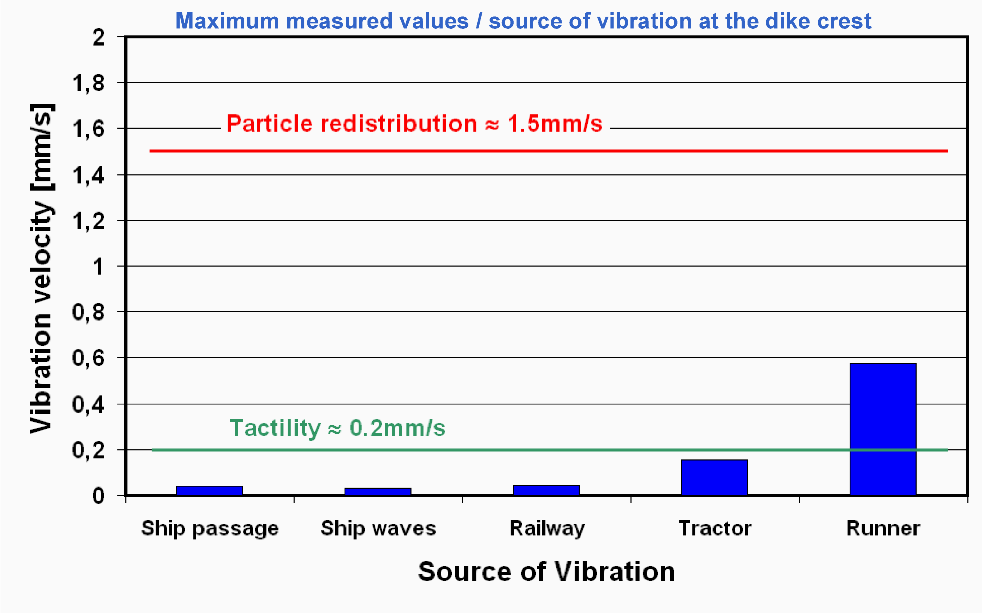


Figure 11. Vibrations of the dike – effect of different sources

6. PORE PRESSURE VARIATIONS IN THE DIKE

The geotechnical investigations covered drilling holes, cone penetration tests, geotechnical laboratory tests and pore pressure measurements. The structure of the soil at the field site is shown exemplarily in Figure 12. The dike is covered by clay with a low permeability of $k_f=1\cdot10^{-8}$m/s. A first clay layer is situated below the dike with a permeability of $k_f=1\cdot10^{-8}$m/s. Therefore, the sandy core of the dike is completely surrounded by clay in this section. A first sand layer with a permeability of $k_f = 3\cdot10^{-5}$ m/s is situated below the upper clay layer. A lower clay layer with a permeability of $k_f=5\cdot10^{-9}$m/s is situated below the first sand layer. Finally, a second sand layer with a permeability of $k_f = 3\cdot10^{-5}$ m/s is situated below the lower clay layer. A more comprehensive geotechnical analysis of the different layers was performed but is not presented here.

Water level variations in front of the dike due to tidal variations, storm surges and ship waves cause pore pressure variations in the dike and the subsoil. No storm surges occurred during the field measurements. Therefore, all water level variations in the dike and the subsoil can be associated either to tidal variations or to ship waves and will be discussed in the following:

(a) Tidal induced Pore Pressure Variations

The tidal wave propagates into the subsoil of the dike. The phreatic line is directed landwards for rising water levels and seawards for falling water levels. The tidal wave amplitude is dampened by the soil and a phase shift from the revetment to the dike can be observed. The attenuation of the tidal wave in the subsoil depends on the permeability of the soil. Figure 13 and Figure 14 show the attenuation of the tidal wave for the upper sand layer and the core of the dike.

A tidal range of Thb = 3.10 m was measured at position LZ3 and decreases behind the revetment (PWD 1_1 and PWD 1_2) and in the upper sand layer to about 1.7 m. Then, the tidal induced pore pressure variation is decreasing from the revetment to the dike down to about 0.3 m (PWD 4_2, 5_2 and 6_2) due to the low permeability of the upper sand layer with a permeability coefficient of $k_f = 3 \cdot 10^{-5}$ m/s. The attenuation of the tidal wave in the lower sand layer is less than in the upper sand layer because of the higher permeability ($k_f = 2 \cdot 10^{-4}$ m/s in the lower sand layer). The tidal induced pore pressure variation is reduced down to about 1.2 m below the dike in the lower sand level (PWD 4_3, 5_3 und 6_3).

Pore pressure variations were also measured in the core of the dike (Figure 14). No tidal induced pore pressure variations were observed in the core of the dike. The measurement results show higher hydrostatic pressures in the core of the dike than in the upper sand level. Therefore, it can be concluded that no hydraulic connection is available between the core of the dike and the subsoil. It can be concluded, that tidal induced pore pressure variations in the dike can not be responsible for the observed settlements of the cover layer of the dike.

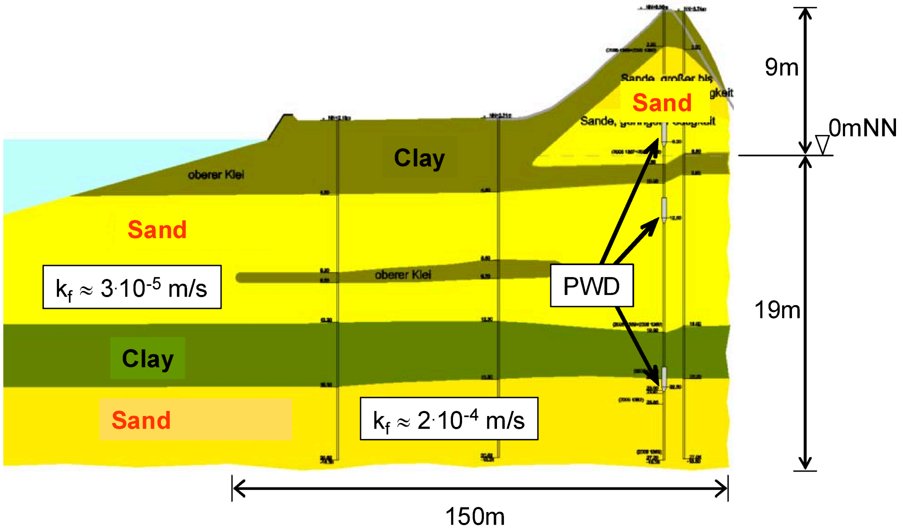


Figure 12. Structure of soil

(b) Ship induced Pore Pressure Variations

The period of the primary wave system is low compared to the period of the tidal wave. Therefore, the propagation of the drawdown wave in the subsoil is reduced compared to the tidal wave. A drawdown wave of about 0.50 m - measured at the position LZ3 - is reduced to a pore pressure variation of about 2 cm (PWD 4_2, 5_3 und 6_3) in the upper sand layer and 3 cm (PWD 4_3, 5_3, 6_3) in the lower sand layer. No significant ship induced pore pressure variations were observed in the dike core.

Secondary waves, having smaller wave periods than the primary wave systems, where not detected in the subsoil (except at position PWD 1_1 just behind the revetment). Therefore it can be concluded, that ship induced effects are of negligible importance for the stability and the deformation of estuarine dikes and the observed failures of the dike are not caused by ship effects.

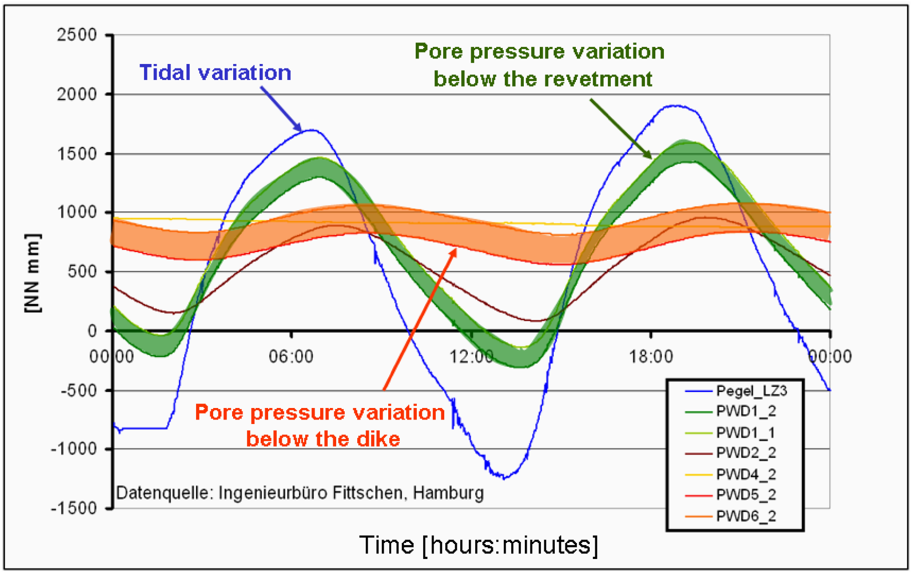


Figure 13. Tidal variations in the upper sand layer

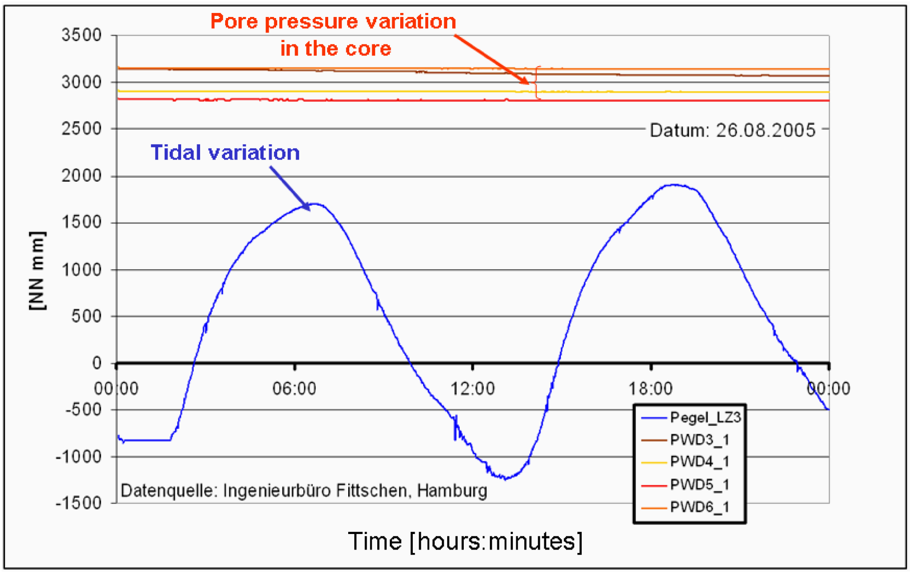
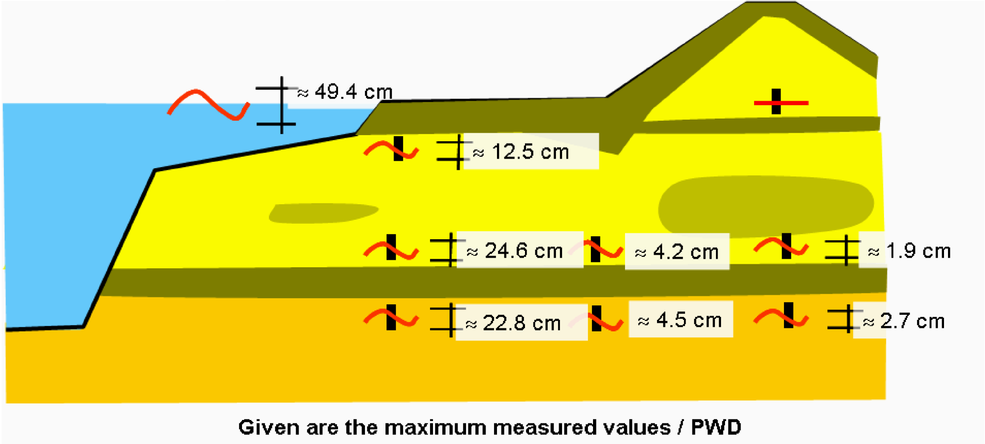


Figure 14. Tidal variations in the core of the dike



Given are the maximum measured values / PWD

Figure 15. Evolution of the drawdown wave in the subsoil (schematic)

7. STABILITY OF THE REVETMENT

The revetment in situ (Figure 16) was partly destroyed during the last years in the lower rubble mound part. The revetment with a slope of 1:n = 1:3 at the field site consists out of a permeable lower part and an impermeable upper part. Failures occurred in the lower rubble mound part. The nominal diameter of the rubble mound is $D_{n,50} = 0.162$ m and $D_{n,50} = 0.292$m with a stone density of $\rho_S = 3.64 \pm 0.10$ t/m^3.

Figure 16. Revetment

The stability of a revetment depends on the wave loads and the resistance of the revetment. The wave loads are described by the height and the steepness of the incoming waves. Wind waves are characterized by the significant wave height H_S and the wave steepness H_S/L_0. Secondary ship waves are specified by the secondary wave height H_{sec} and the associated wave steepness H_{sec}/L_0. The local wave climate was described in section 4 by fitting statistical functions. In addition, the water level distribution, the density of the water and the rubble mound were also described by fitting normal density functions. The assessment of the failure probability is performed by defining a limit state equation:

$$z = k_D^{1/3} \cdot D_{n50} \left(\frac{\rho_S}{\rho_W} - 1 \right) n^{1/3} - H$$

with:

z = limit state function

k_D = dimensionless stability coefficient

The calculation of k_D was performed according to Verhey and Bogaerts (1989) for secondary ship waves and Pilarczyk (1992) for wind waves. It was concluded from deterministic analysis, that the existing rubble mound diameter is partly too small to resist both, wind waves and ship waves. It was concluded from probabilistic analysis, that the failure probability of wind waves is higher than the failure probability of ship waves. Details on the probabilistic and the deterministic calculations of the stability analysis are not given here.

7. SUMMARY AND CONCLUSIONS

The notion of tidal waves, wind waves and ship waves is relevant for the interaction between hydrodynamic loadings and geotechnical processes of estuarine structures such as revetments, dikes and groins and also for the design of these structures.

The present paper describes field measurements to investigate the influence of ship induced loads on dikes and revetments in the Elbe estuary in Germany. The field measurements were motivated by observed failures of the dike and the revetment. Ship induced processes were made responsible for the observed failures by the local authorities. Therefore, the BAW was commissioned to investigate the influence of ship induced processes on the stability of the dike and the revetment to explain the observed failures.

The influence of ship-induced processes is described in the present paper. It can be shown by field measurements, that ship induced processes such as pore pressure variations or vibrations can not be the reason for the observed dike failures. The amplitudes of ship induced pore pressure variations or vibrations in the dike are small compared to other loads. Nevertheless, the failures of the revetment can be partly explained by the effect of ship waves but also by wind waves.

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