DPWA Winners
2021
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INTRODUCTION

Biotic components of coastal ecosystems are increasingly incorporated in coastal defence against erosion and floods. In contrast, conventional protective structures such as sea dykes, seawalls, revetments, groins and detached breakwaters are increasingly perceived as coastal armouring which may significantly affect cultural and other types of ecosystem services. Despite this pervasive perception, the application of these ‘hard’ solutions and their maintenance are expected to rather increase. In fact, they are also still perceived as the most efficient coastal protection against extreme events, particularly in urban areas and in many other cases where softer alternative solutions for managing coastal erosion and floods are unfeasible. Therefore, besides the diverse solutions to ecologically enhance these ‘hard’ structures, the introduction of vegetation as an integral constituent of coastal defence schemes has also long reached maturity for wider practical applications, and best practice recommendations are beginning to emerge [Feagin, 2008; Gedan et al., 2011]. In the latter case, a reliable prediction of wave damping by vegetation might be crucial for the safety of the hinterland. This is particularly the case where vegetation (e.g. seagrass, saltmarsh) is introduced in the foreshore to reduce the height/mass of conventional structures by damping the waves before reaching the latter. There are indeed diverse models and simplified formulae suitable for practical applications to predict with a relatively good engineering accuracy the damping efficacy of vegetation under either pure waves or pure current conditions. Most of these formulae are based on the assumption of stiff plants and/or the effect of plant flexibility is considered by introducing a reduction factor to account for flow resistance. Though combined waves and currents are ubiquitous in coastal areas, particularly in tidal coasts, it is rather surprising that only very few studies have been dedicated to the effect of currents on wave damping by vegetation, some even with contradictory results [Li and Yan, 2007; Paul et al., 2012; Hu et al., 2014; Losada et al., 2016]. Adding the effect of plant flexibility, the wave attenuation becomes even more complicated due to the complex wave-current-vegetation interactions (Figure 1).
Figure 1: Processes involved in the interactions of flexible vegetation, waves and current. The plant meadow reduces wave height and mean flow velocity by absorbing energy from the flow through drag and turbulent dissipation. Flexible vegetation reconfigures under the influence of water flow depending on the vegetation attributes (\( h_p \) and \( h_{pd} \) show the plant height and deflected plant height, respectively).

These generally strong and highly complex ‘triplet interactions’ might be the reason why no physically-based prediction formulae for engineering applications are yet available to predict wave attenuation by flexible vegetation under wave-current conditions.

With this background, the overarching goal of this study is therefore to improve the understanding of the physical processes and the relative importance of the hydraulic and vegetation parameters which affect wave attenuation by submerged flexible vegetation under wave-current conditions and, based on this improved understanding, to develop new prediction formulae which account for the most relevant influencing parameters. More specifically, it aims at:

(i) selecting the most appropriate CFD model to be used in this study and at improving/validating it to simulate wave attenuation by stiff vegetation under pure waves and wave-current conditions,

(ii) extending this CFD model for wave attenuation by flexible vegetation,

(iii) using this CFD model for a systematic parameter study to determine the relative importance of the hydraulic and vegetation parameters, and

(iv) developing new formulae for the prediction of wave attenuation by stiff and flexible vegetation under pure waves and wave-current conditions based on the analysis of the data and the insight into the underlying processes gained from the parameter study.

### 2 CFD MODEL FOR STIFF VEGETATION

A numerical wave flume using the CFD model in OpenFOAM® is set up, calibrated and validated for the study of wave attenuation by stiff vegetation under pure waves and wave-current conditions. The four main steps of this modelling process are depicted in Figure 2.
Step 1: Selection of the most appropriate CFD model for waves through vegetation

For the modelling of wave propagation through vegetation, the CFD solver ‘PorousWaveFoam’ in the frame of OpenFOAM® [Jensen et al., 2014] is selected. This model solves the Volume-Averaged Reynolds-Averaged Navier–Stokes (VARANS) equations for the simulation of flow in porous media without representing the exact geometry of the pores forming the porous media using the Volume Of Fluid (VOF) method for free surface tracking. A description of the governing equations used for the selected CFD solver ‘PorousWaveFoam’, including RANS-VOF for free surface tracking, VARANS for the flow in porous media, the ‘waves2Foam’ toolbox for wave generation and the RANS type of the k-ω-SST model for turbulence can be seen in Hadadpour et al. (2019, 2021) and Hadadpour (2020).

Step 2: Application of a porous media approach for a vegetation field

For applying a porous media approach for a vegetation field, the ‘hydraulic’ properties of the vegetation meadow, including porosity \( n \) and characteristic length scale \( D \), are required in the Darcy-Forchheimer sink term of the VARANS equations. Vegetation fields are naturally characterized by high porosities (often more than 0.97) and low solid fractions. Hence, a more practical parameterisation is carried out and an ‘equivalent porosity’ \( n_{eq} \) is proposed to replace porosity \( n \) in the VARANS equations while the distance between the plants \( \Delta S \) is defined as a new length scale for the new approach. For this purpose, since the mesh quality affects the accuracy of the numerical simulation results, firstly a sensitivity analysis is performed to determine the “optimum” mesh size leading to a mesh independent solution, i.e. one for which accuracy is not altered when mesh refinement is increased [Hadadpour, 2020].

To obtain the proper porosity of vegetation \( n_{eq} \), the CFD model is set up and calibrated according to laboratory tests of wave attenuation by submerged stiff vegetation from four different studies [Bouma et al., 2005 ; Paul et al., 2012 ; Ozeren et al., 2014 ; Hu et al., 2014]. The new equivalent porosity \( n_{eq} \) is developed as a function of dimensionless frontal area per bed area \( A_{front}^* = N d h_p \), where \( N \) is plant density, \( d \) is plant width perpendicular to flow direction and \( h_p \) is plant height. It is a physically well-defined and measurable parameter of the vegetation field (see more details in Hadadpour et al. (2019) and Hadadpour (2020)):

\[
n_{eq} = 1 - 0.22 (A_{front}^*)^{0.51}
\]

Step 3: Model validation under pure wave conditions

The validation is based on the wave damping factor \( \gamma \) (m\(^{-1}\)) of the hyperbolic decay law derived by Dalrymple et al. (1984) using linear wave theory for wave attenuation by stiff vegetation:

\[
K_x = \frac{H_x}{H_i} = \frac{1}{1 + \gamma x}
\]

\( H_x \) and \( H_i \) are the wave height at propagation distance in the vegetation meadow and the incident wave height at \( x=0 \), respectively. \( K_x \) is the damping coefficient and \( \gamma \) (m\(^{-1}\)) is a parameter depending on the vegetation and wave characteristics.

For the validation, two set of laboratory experiments [Bouma et al., 2010 ; Hu et al., 2014] have been used. A comparative analysis of damping factor \( \gamma \) obtained from the CFD model and from the laboratory tests using four statistical indicators (i.e. Bias, Root Mean Square Error RMSE, correlation coefficient \( R \) and Willmott Index) indicates a very good agreement between numerical and experimental results (Figure 3).
Step 4: Model validation under wave-current conditions

For model validation under wave-current conditions, the experiments of Hu et al. (2014) are used. The validation is based on the comparative analysis of the wave height reduction per unit distance $\Delta H$ (m/m) by stiff vegetation measured in the experiments and $\Delta H$ obtained from the CFD model for regular waves with an underlying current (0.05-0.3 m/s) in the same direction as the waves:

$$\Delta H = \frac{(H_{in} - H_{out})}{B_m}$$  \hspace{1cm} (3)

$H_{in}$ and $H_{out}$ are the wave heights at the beginning and end of the vegetation meadow, respectively and $B_m$ is the meadow length. Figure 4 and the embedded tables with the statistical indices show that a relatively good agreement is achieved between computed and measured $\Delta H$ values and the model performs relatively well for wave attenuation by stiff vegetation under different wave-current conditions.
Figure 4: Scatter-plot of measured (Hu et al., 2014) and computed wave height reduction per unit distance inside stiff vegetation $\Delta H$ (m/m) for combined waves with: (a) 0.05 m/s, (b) 0.15 m/s, (c) 0.20 m/s and (d) 0.30 m/s current in the same direction. VD1 and VD2 indicate vegetation densities of 62 and 139 stems/m$^2$, respectively.

3 EXTENSION OF THE CFD MODEL FOR STIFF VEGETATION TO ACCOUNT FOR FLEXIBLE VEGETATION

The validated CFD model for stiff vegetation in the previous section is extended and validated for flexible vegetation by considering the bending of the plant stems and its effect on wave attenuation. The four main steps to achieve this goal are shown in Figure 5.

Step 1: Selection of the most appropriate approach to model the deflection of the plant stems as a compromise between accuracy/sophistication and computational efficiency

In this study, the impact of plant reconfiguration on wave attenuation is characterised in terms of drag force, which depends on the flow velocity and the projected area normal to the flow direction. Hence, the fluid load-deflection relationship can be applied to calculate the deflected height and the actual projected area affecting vegetation-induced flow resistance.

Therefore, the formulation for large deflections by Li and Xie (2011) is selected as the deflection of vegetation with high flexibility can be predicted accurately by a large deflection analysis based on the Euler-Bernoulli Law for the bending of a slender beam. Moreover, this approach is favoured because the extended CFD model is to be applied (i) for high hydrodynamic loads and large plant deflections, and (ii) for a very extensive parameter study (see Section 4 below); hence it is compromise between model accuracy/sophistication and computational efficiency. For the equations and more details see Hadadpour (2020).
Step 2: Extension of the CFD model for stiff vegetation to account for flexible vegetation

The deflected plant height defined as the actual height that affects the flow due to plant bending is considered as the most important parameter in the energy dissipation associated with the drag force on the vegetation. In this sense, the aforementioned formulation by Li and Xie (2011) is introduced in the extended model to calculate the reduction of the plant height resulting from its large deflection (Figure 6).

![Figure 6: Solving procedure of the extended model system for wave attenuation by introducing flexible vegetation](image)

In the present approach, the wave model, which considers the vegetated region as a porous media continuum using VARANS equations, is first solved. The vegetation deflection is calculated based on the drag force exerted on the plant stem located at the first row of the vegetation field, which experiences maximum velocity values and thus maximum deflection within the vegetation field. The fluid domain is then modified accordingly and fed back to the wave model to calculate new flow velocities and surface elevation. The two models are hence coupled through the vegetation-induced hydrodynamic forces. Moreover, the proposed coupling approach makes it possible to replace any of the coupled models with alternative solvers without having to adapt the remaining solver.

Step 3: Validation of the extended CFD model for flexible vegetation under pure wave conditions

The validation is based on the comparative analysis of the dimensionless parameter \( K_D a_0 \lambda \) (m\(^2\)/m\(^2\)) measured in the experiments of Luhar et al. (2017) and \( K_D a_0 \lambda \) calculated from the CFD model:

\[
\frac{a}{a_0} = \frac{1}{1 + K_D a_0 \lambda} \quad (4)
\]

where \( a_0 \) is the initial wave amplitude at \( x=0 \) and \( K_D \) is a parameter depending on the vegetation frontal area per unit volume, the drag coefficient, the wave number and the water depth (see Equation 7 in Luhar et al. (2017)).

The CFD model is shown to reproduce relatively well the wave height evolution over the vegetation field and the damping coefficient. As seen from Figure 7 and the four statistical indicators in the embedded table, it may be concluded that the wave height attenuation by flexible vegetation can be predicted by the extended model within the range of common engineering accuracy.

![Figure 7: Scatter-plot of calculated \( K_D a_0 \lambda \) (m\(^2\)/m\(^2\)) from measured data (\( K_D a_0 \lambda \)\(_m\)) [Luhar et al., 2017] and simulated data (\( K_D a_0 \lambda \)\(_s\)) (present model) using Equation 4 for different wave and vegetation conditions](image)
Step 4: Validation of the extended CFD model for flexible vegetation under wave-current conditions

The model is then validated for wave attenuation under wave-current conditions based on linear assumption of wave attenuation (Equation 3) to make the results comparable with the experiments of Paul et al. (2012). According to Figure 8 and the statistical indicators in the embedded table, the model performs relatively well in simulating wave attenuation by flexible vegetation under wave-current conditions. However, the tentative validation is based on a limited number of data with moderate hydrodynamic conditions due to the lack of appropriate experimental data.

According to Figure 8 and the statistical indicators in the embedded table, the model performs relatively well in simulating wave attenuation by flexible vegetation under wave-current conditions. However, the tentative validation is based on a limited number of data with moderate hydrodynamic conditions due to the lack of appropriate experimental data.

4 SYSTEMATIC PARAMETER STUDY: SELECTED RESULTS

Overall, previous studies have shown that wave attenuation by vegetation is highly dependent on both hydrodynamic conditions and vegetation properties including individual plant and meadow characteristics. Regarding these diverse dependencies and also the extensive variety of coastal plants, a high variability of wave attenuation by vegetation would be expected; hence more investigation is required to analyse the underlying processes and influencing parameters. Therefore, an extensive parameter study with around 300 numerical tests is performed and the results are analysed in order (i) to better understand the relative importance of the effects of the key parameters and underlying processes influencing wave attenuation by stiff and flexible vegetation under both pure wave and wave-current conditions, and (ii) to develop wave attenuation formulae as a function of the most relevant parameters for both types of vegetation under both types of flow conditions.

To this end, the effect of the following seven parameters on wave attenuation by stiff and flexible vegetation are considered: vegetation density $N$ (stem/m$^2$), submergence ratio $h/h_p$, relative meadow length $B_m/L_w$, vegetation stiffness $EI$, incident wave height $H$ and wave period $T$, and following current velocity $U_c$. In addition, the combined effects of these parameters on wave attenuation is also quantified. The range of variation of these parameters in the numerical tests is meaningfully based on the values considered in the most relevant studies. For more details including different test conditions, see Hadadpour (2020) and Hadadpour et al. (2021). Results of the extensive parameter study reveal that wave attenuation increases with increasing plant density $N$, plant height $h_p$, plant stiffness $EI$ and meadow length $B_m$; however, the effect of plant height $h_p$ dominates. Regarding the effect of wave parameters, wave attenuation increases with increasing incident wave height $H$, increasing wave period for $B_m/L_w=1$, and decreasing wave period for $B_m=3.1$ m. Overall, the effect of vegetation characteristics appears to be more influential than that of the wave parameters. The main results are briefly summarised in Table 1 supported by Figures 9-12.
### Effect on wave attenuation and relative importance

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<td><strong>Vegetation characteristics</strong></td>
<td>- <em>Plant height</em> ($h_p$): Wave attenuation increases with increasing plant height $h_p$ under a constant water depth, i.e. decreasing submergence ratio $h/h_p$, for both stiff and flexible vegetation (Figures 9, 10 and 11a)</td>
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<td>- <em>Plant density</em> ($N$): wave attenuation increases with increasing plant density $N$ for both stiff and flexible vegetation (Figures 9 and 11a)</td>
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<td>- <em>Plant stiffness</em> ($EI$): Wave attenuation increases with increasing stiffness $EI$ for the same wave forcing (Figures 10 and 11a)</td>
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<td>- <em>Length of vegetation field</em> ($B_m$): Wave attenuation increases with increasing meadow length $B_m$ under the same wave conditions for both stiff and flexible vegetation (Figure 9)</td>
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<td><strong>Wave parameters</strong></td>
<td>- <em>Incident wave height</em> ($H_i$): Wave attenuation increases with increasing incident wave height $H_i$ for both stiff and flexible vegetation (Figure 10)</td>
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<td>- <em>Incident wave period</em> ($T$): For both stiff and flexible vegetation, increasing the wave period $T$ results in higher wave attenuation when the analysis is based on a constant relative meadow length $B_m/L_w=1$ (Figure 5-19 in Hadadpour (2020)). While, conversely, the wave attenuation decreases with increasing the wave period when the wave height reduction is considered over a constant meadow length $B_m=3.1$ m (Figure 5-20 in Hadadpour (2020))</td>
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<td><strong>Combined effects of the diverse parameters</strong></td>
<td>- Plant height $h_p$ and hence, submergence ratio $h/h_p$, appears to be more influential than plant density $N$ on wave attenuation (Figure 11a)</td>
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<td>- Plant stiffness $EI$ and density $N$ can compensate each other depending on the submergence ratio $h/h_p$, i.e. flexible vegetation at higher densities might be able to induce the same wave height reduction as stiff vegetation at low densities (Figure 11a)</td>
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<td>- The impact of meadow length $B_m$ on wave attenuation increases with increasing plant density $N$ and decreasing submergence ratio $h/h_p$; however, the effect of submergence ratio dominates (Figure 9)</td>
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<td>- The impact of incident wave height $H_i$ increases with decreasing plant density $N$ and increasing submergence ratio $h/h_p$, i.e. decreasing plant height $h_p$ under a constant water depth $h$ (Figure 11b)</td>
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<td>- The effect of vegetation characteristics is likely more significant than that of the wave parameters (Figure 11b)</td>
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<td><strong>Following current</strong></td>
<td>- The impact of a following current on wave attenuation can be seriously affected by submergence ratio $h/h_p$ (Figure 5-23 in Hadadpour (2020))</td>
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<td>- For almost all tested cases, a following current causes a decrease of the wave-attenuating capacity of vegetation. This decrease becomes more significant with increasing current velocity $U_c$ (Figures 5-22 and 5-23 in Hadadpour (2020))</td>
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<td>- For a very sparse stiff meadow ($N=139$ stem/m²), a following current can increase the wave height attenuation depending on the incident wave and current velocity (Figure 5-31 in Hadadpour (2020))</td>
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<td>- The current presence does affect wave propagation depending on the rate of change of velocity amplitude ($U_r=U_{cr}/U_{pw}$), which defines the change of velocity amplitude in the presence of currents $U_{cr}$ compared to pure waves $U_{pw}$, which may differ as a function of the wave and vegetation characteristics (Figure 12)</td>
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<td>- Wave height attenuation decreases with increasing $U_r$, while it increases with decreasing $U_r$ (Figure 12)</td>
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Table 1: Effects of individual and combined parameters on the wave-attenuating capacity of vegetation based on the results of the parameter study, including their relative importance
Figure 9: Effect of relative meadow length $B_m/L_w$ on $H_{\text{reduction}}$ for flexible ($EI = 2.4 \times 10^{-6} \text{ N.m}^2$) vegetation field with different plant densities $N$ and submergence ratios $h/h_p$ and a constant wavelength $L_w=3.1 \text{ m}$ for $B_m/L_w=0.5$ to 3. $H_{\text{reduction}}$ shows the wave height reduction at the end of vegetation field $H_{\text{reduction}}(\%) = \left( \frac{H_{\text{front}}-H_{\text{behind}}}{H_{\text{front}}} \right) \times 100$.

Figure 10: Effect of relative incident wave height $H_i/h$ on $H_{\text{reduction}}$ for stiff (empty bars) and flexible (filled bars) vegetation field with length $B_m=3.1 \text{ m}$, plant density $N=1000 \text{ stems/m}^2$ and different submergence ratios $h/h_p$ for $H_i/h=0.16$ to 0.3. $H_{\text{reduction}}$ shows the wave height reduction at the end of vegetation field $H_{\text{reduction}}(\%) = \left( \frac{H_{\text{front}}-H_{\text{behind}}}{H_{\text{front}}} \right) \times 100$. 

Flexible and rigid vegetation
Figure 11: Combined effects of the diverse parameters including (a) effect of submergence ratio \( h/h_p \) on the relationship between \( H_{\text{reduction}} \) and plant density \( N \) for stiff and flexible \( (EI = 2.4 \times 10^{-6} \text{N.m}^2) \) vegetation field, (b) effect of submergence ratio \( h/h_p \) on the increasing effect of relative incident wave height \( Hi/h \) on \( H_{\text{reduction}} \) for flexible vegetation field with length \( B = 3.1 \text{ m} \) with different plant density \( N \). Wave attenuation \( H_{\text{reduction}} \) shows the wave height reduction at the end of vegetation field \( H_{\text{reduction}}(\%) = \left( \frac{H_{\text{front}} - H_{\text{behind}}}{H_{\text{front}}} \right) \times 100 \). Relative percentage change shows the relative increase between wave height reduction \( H_{\text{reduction}} \) for \( Hi/h=0.16 \) and \( Hi/h=0.3 \), i.e. Relative percentage change \( (\%) = \left( \frac{(H_{\text{reduction}})_{Hi/h=0.3} - (H_{\text{reduction}})_{Hi/h=0.16}}{(H_{\text{reduction}})_{Hi/h=0.16}} \right) \times 100 \)

Figure 12: Relative wave height decay \( r_w = \frac{(H_{\text{reduction}})_{\text{wave-current}}}{(H_{\text{reduction}})_{\text{pure-wave}}} \) vs rate of velocity amplitude changes in current presence \( U_r = \frac{U_{cw}}{U_{pw}} \), which defines the change of velocity amplitude in the presence of currents \( U_{cw} \) compared to pure wave conditions \( U_{pw} \), for both stiff and flexible \( (EI = 2.4 \times 10^{-6} \text{N.m}^2) \) vegetation field with different plant densities \( N \) and submergence ratios \( h/h_p \) under various combinations of waves and currents

Hu et al. (2014) concluded that a following current may increase or decrease wave attenuation by vegetation depending on velocity ratio \( \alpha = \frac{U_c}{U_w} \); \( U_c \) and \( U_w \) are the current velocity and the horizontal orbital velocity, respectively. They also attributed the inconsistency of previous studies to different ranges of this ratio in their investigations (e.g. \( \alpha = 1.5 \text{–} 3.5 \) in Li and Yan (2007) and \( \alpha < 0.5 \) in Paul et al. (2012)). In the present study, for almost all tested cases with a wide range of velocity ratio \( \alpha = 0.3 \text{–} 8.0 \), the presence of a following current causes a decrease of the wave-attenuating capacity of vegetation, which is in agreement with the previous findings in Paul et al. (2012) and Losada et al. (2016). However, the results might not be directly comparable to those by Hu et al. (2014) because the latter increased the generated incident wave height in the wave-current tests for different current velocities which may enhance wave attenuation. Moreover, wave and current velocities were linearly superposed without accounting for their nonlinear interaction. Furthermore, only the frontal area per canopy
volume was considered for comparing their tests with others, but without considering plant density, which may strongly affect the flow patterns around the meadow as well as the flow penetration within the vegetation meadow.

In this study, therefore, a very sparse rigid meadow with plant density \( N=139 \) stems/m\(^2\) is also tested to make it comparable to that of the VD2 tests in Hu et al. (2014), which shows that a following current can indeed increase wave attenuation over a sparse vegetation field. This is likely due to the non-linearity effect caused by wave deformation in non-linear wave-current interaction as well as the attenuation effect of vegetation.

In this respect, Figure 13 compares the horizontal velocity component \( U_x \) and the flow patterns for reference case (i.e. without vegetation) as well as a submerged vegetation meadow with plant densities \( N=100 \) and 1,000 stems/m\(^2\) under combined wave-current conditions. The horizontal velocity \( U_x \) according the Stokes second order theory [Svendsen and Jonsson, 1976] is given as below:

\[
U_x = U_c + \frac{H}{2} \frac{g k}{\omega_{w,c} \cosh kh} \cos(kx - \omega_w t) + \frac{3}{16} \frac{H^2 \omega_{w,c} k \cosh 2k(z + h)}{\sinh^4 k h} \cos 2(kx - \omega_w t) \tag{5}
\]

where \( U_c \) is the uniform current velocity, \( H \) is the wave height, \( g \) is acceleration due to gravity and \( h \) is the water depth. \( z \) and \( t \) represent the vertical coordinate and time, respectively. The quantity \( x \) is the distance along longitudinal direction. \( \omega_{w,c} \) represents the frequency of the wave-current, \( \omega_{w,c} = \omega_w - k. U_c, \omega_w \) and \( k \) are the wave angular frequency and the wave number.

As shown in Figure 13, the flow pattern can be significantly influenced by the presence of submerged vegetation, especially for a relatively dense vegetation meadow with \( N=1,000 \) stem/m\(^2\) due to their capacity to induce larger current blocking, thus causing current to diverge vertically over the meadow instead of passing through it. For strong currents with velocity \( U_c=0.2 \) m/s, the difference of flow velocity above and below the vegetation meadow is extremely high.

![Figure 13: Effect of plant density N and current velocity Uc on the flow pattern in/near a rigid vegetation meadow for reference case (i.e. without vegetation) as well as a submerged mimic meadow with different plant densities N=100 and 1,000 stems/m^2 for wave-current conditions with wave H=0.08 m, T=1 s in 0.5 m water depth following the currents with different velocities Uc=0, 0.05, 0.1 and 0.2 m/s. The black area indicates the vegetation meadow B_m=1.5 m and h_p=0.3 m, and the white lines represent streamlines.](image)

In this sense, a shear layer can be generated at the water-vegetation interface due to the flow velocity difference above and below the vegetation meadow, where Kelvin-Helmholtz (KH) instability may develop [Ghisalberti and Nepf, 2002]. This instability may form coherent vortices within the mixing layer (in dense vegetation meadow with \( N=1000 \) stem/m\(^2\)), which dominate the vertical momentum transfer across the water-vegetation interface.
5 DEVELOPMENT OF A WAVE ATTENUATION FORMULAE FOR FLEXIBLE VEGETATION

Based on the data and insight obtained from the results of the parameter study in Section 4, a set of prediction formulae for wave attenuation by both stiff and flexible submerged vegetation under both pure wave (Phase 1) and wave-current conditions (Phase 2) is developed for the first time.

Phase 1: Wave attenuation formulae for flexible vegetation under pure wave conditions

The development is performed in four main steps summarised in Figure 14.

- **Step 1:** Deriving a new prediction formula for wave height reduction by stiff vegetation under pure wave conditions \((\text{H}_{\text{reduction}})_{R}\) based on the results of the numerical parameter study
  - Validating the new formula \((\text{H}_{\text{reduction}})_{R}\) using experimental data
- **Step 2:** Determining the effective deflected height of flexible vegetation \(h_{e}\) as a function of the Casually number (Cn) and blade length ratio (L) based on the scaling law for individual isolated plants
- **Step 3:** Determining the effective plant height within a meadow \(h_{m}\) based on the effective plant height in isolation \(h_{e}\) obtained in step 2
  - Replacing \(h_{m}\) by plant height \(h_{p}\) in the proposed formula in Step 1 to calculate wave height reduction by flexible vegetation meadow under pure wave conditions \((\text{H}_{\text{reduction}})_{F}\)
  - Validating the new formula \((\text{H}_{\text{reduction}})_{F}\) using experimental data

**Figure 14:** Steps of the procedure to derive a new prediction formula for wave attenuation by flexible vegetation under pure wave conditions

**Formula for wave attenuation by stiff vegetation under pure wave conditions \((\text{H}_{\text{reduction}})_{R}\):** The formula is derived based on multiple regression analysis as a function of five dimensionless parameters \((A_{\text{front}}, \frac{h_{p}}{h}, \frac{B_{m}}{L_{w}}, \frac{h}{H}, \frac{h}{L_{w}})\) determined from the parameter study. The relative importance of these independent variables are compared in the scatterplot matrix (Figure 15).

**Figure 15:** Scatterplot matrix (upper diagonal elements) and correlation matrix (lower diagonal elements) which show the relationships between wave attenuation by rigid vegetation under pure wave conditions and the effective parameters identified in the parameter study
The findings of the regression analysis, namely that the correlation of \((H_{\text{reduction}})_{\text{R}}\) is strongest with \(h^{WR}\) while it is negative and positive for the four other parameters \((H_i/h, h/L_w, B_m/L_w, A_{\text{front}}^*)\), are confirmed by the scatter matrix:

\[
(H_{\text{reduction}})_{\text{R}} = 11.5 (A_{\text{front}}^*) + 37.5 (H_i/h) + 61 (h^{WR}_M) - 70.3 (h/L_w)
\] (6)

This formula is validated against laboratory experiments, showing that it performs relatively well in predicting wave attenuation by stiff vegetation (Figure 16).

**Figure 16: Comparison of the measured [Keimer et al., 2021] and calculated (Equation 6) wave height reduction by stiff vegetation \(H_{\text{reduction}}\) under pure wave conditions, the blue line shows 1:1 line**

Effective deflected height of a flexible plant in isolation \(h_e\): \(h_e\) is calculated as a function of the Cauchy number \(Ca\) and blade length ratio \(L\) based on the scaling law for individual isolated plants using the formulation presented by Lei and Nepf (2019a):

\[
\frac{h_e}{h_p} = (0.94 \pm 0.06)(Ca L)^{-0.25 \pm 0.02}, \quad 1 < (Ca L) < 10000
\] (7)

Effective height of a flexible plant within a meadow \(h_{e,m}\): \(h_{e,m}\) is calculated based on \(h_e\) and the difference between the effective plant height in isolation and in a meadow \(h_{r,m}\), which is obtained as a function of plant density \(N\) and plant height \(h_p\), as follows:

\[
h_{e,m} = h_e + h_{r,m} = 0.94(Ca L)^{-0.25} \times h_p + 0.64(A_{\text{front}}^*)^{0.22} \left(\frac{h_p}{h}\right)^{0.94} \times h_p
\] (8)

The new formula for wave attenuation by flexible vegetation under pure wave conditions \((H_{\text{reduction}})_{\text{F}}\) is obtained by replacing plant height \(h_p\) in Equation 6 by effective height \(h_{e,m}\) calculated from Equation 8.

\[
(H_{\text{reduction}})_{\text{F}} = 11.5 (N \times d \times h_{e,m}) + 37.5 (H_i/h) + 61 (h^{WR}_M) (B_m/L_w) - 70.3 (h/L_w)
\] (9)

Validation of a new wave attenuation formula for flexible vegetation \((H_{\text{reduction}})_{\text{F}}\): two set of small-scale and large-scale experiments are used for validation. As shown in Figure 17, the formula performs well in predicting small-scale experiments, while the data shows more scatter for large-scale experiments. This might be attributed to the fact that the CFD model, from which the numerical data used for the multiple regression analysis to develop the new formula are obtained, was calibrated and validated mainly using data from small-scale experiments.
Figure 17: Comparison of the calculated (using Equation 9) and measured from (a) large-scale experiments by Manca et al. (2012), (b) small-scale experiments by Luhar et al. (2017) wave attenuation by flexible vegetation under pure wave conditions ($H_{\text{reduction}}^F$).

Phase 2: Wave attenuation formulae for flexible vegetation under wave-current conditions

The development is performed in four main steps as summarised in Figure 18.

Figure 18: Steps of the procedure to derive a new prediction formula for wave attenuation by flexible vegetation under wave-current conditions

Formula for the relative wave attenuation by stiff vegetation in wave-current conditions and pure wave conditions ($r_w^R$) is obtained as a function of the most relevant parameters from the parameter study:

$$
(r_w^R) = 0.024 \left(\frac{A_{\text{front}}^*}{R_F}\right) + 0.083 \left(\frac{h_p}{h}\right) - 8.47 \left(\frac{h_p}{h}\right) \left(\frac{U_c}{U_w}\right) \left(\frac{H_i}{L_w}\right) + 0.011 \left(\frac{A_{\text{front}}^*}{R_F}\right) + 0.81
$$

Formula for the wave attenuation by stiff vegetation under wave-current conditions ($H_{\text{reduction}}^{\text{wave-current}}$) is calculated based on ($r_w^R$) from Equation 10 and wave attenuation by stiff vegetation under pure wave conditions ($H_{\text{reduction}}^R$) according to Equation 6:

$$
(H_{\text{reduction}}^{\text{wave-current}}) = (r_w^R) \times (H_{\text{reduction}}^R)
$$

Formula for the ratio of wave attenuation by flexible vegetation ($H_{\text{reduction}}^{\text{wave-current}}$) to that induced by stiff vegetation ($H_{\text{reduction}}^{\text{wave-current}}$) under wave-current conditions: it is obtained as a function of dimensionless parameters ($\frac{h_c}{h_p}, \frac{\Delta s}{d}$) based on the proposed porous media approach in the sense that the effect of flexible...
vegetation on energy dissipation is a reduction of the drag force due to plant reconfiguration, which results in a reduced frontal area of the vegetation:

\[
\frac{(H_{\text{reduction}}_{\text{wave-current}})_F}{(H_{\text{reduction}}_{\text{wave-current}})_R} = 1.57 \left( \frac{h_e}{h_p} \right)^{0.15} \left( \frac{\Delta S}{d} \right)^{-0.16}
\]  

(12)

The effective plant height \(h_e\), defined as the height of a stiff plant that generates the same energy dissipation as the flexible plant of height \(h_p\), is obtained from the equation proposed by Lei and Nepf (2019b) for combined wave-current conditions.

Formula for the wave attenuation by flexible vegetation under wave-current conditions \((H_{\text{reduction}}_{\text{wave-current}})_F\): it is calculated based on \((H_{\text{reduction}}_{\text{wave-current}})_F\) from Equation 12 and \((H_{\text{reduction}}_{\text{wave-current}})_R\) according to Equation 11:

\[
(H_{\text{reduction}}_{\text{wave-current}})_F = \left( \frac{(H_{\text{reduction}}_{\text{wave-current}})_F}{(H_{\text{reduction}}_{\text{wave-current}})_R} \right) \times (H_{\text{reduction}}_{\text{wave-current}})_R
\]  

(13)

To the best of the author’s knowledge, there is no appropriate experimental data, which fulfil the requirements of the proposed model and formula to validate the new prediction formula. Hence, Figure 19 indicates the comparison of the calculated (Equation 13) with simulated (CFD model) wave attenuation by flexible vegetation under wave-current conditions for all tested cases in the parameter study. As shown in Figure 19 and the embedded table, it may be concluded that the wave attenuation by flexible vegetation under wave-current conditions can be predicted reasonably well (within ±15 %) by the proposed new formula (Equation 13).

![Figure 19: Scatter plot of calculated (Equation 13) and simulated (CFD model) wave attenuation over a flexible vegetation meadow under wave-current conditions for all tested cases in the parameter study (see Table 5-7 in Hadadpour (2020)). The solid line shows the perfect 1:1 line and dashed lines show the 15% error margins.](image)

6 POTENTIAL CONTRIBUTION OF THE PROPOSED APPROACHES TO ADVANCE THE SCIENTIFIC KNOWLEDGE AND TOOLS

Despite the gradual growth of available approaches on the development of nature-based solutions for coastal protection which are appropriate to adapt to climate changes, further modelling and engineering assessments of the efficiency of natural protection are still needed to better understand the potential of vegetation in shore protection. In this sense, field observations can provide valuable data under realistic conditions; however, they are difficult to perform; yet, they also have some limitations such as controlling hydrodynamic conditions and vegetation characteristics or replicating the tests. Besides, several laboratory studies have been carried out to study wave-vegetation interaction under controlled conditions. This particularly underlines the potential applications of the proposed modelling approach. The latter can indeed provide useful results with less costs and efforts than laboratory testing, and contribute to advance the scientific knowledge and tools which are required for a safer and more effective implementation of the ‘Working with Nature philosophy’ of PIANC.
In this scope, some benefits of the present model approach deserve to be highlighted: (i) despite the complicated vegetation structure and despite some simplifying assumptions, the use of $A_{\text{front}}^*$ in the relationship for the equivalent porosity represents an important step in the proposed porous media approach for vegetation, (ii) the model is easy to use and relatively fast, because the vegetation field is presented as a porous block in this model and there is no need to generate a complicated mesh to model the plants, (iii) the model calibration is based on only one parameter (i.e. equivalent porosity $n_{\text{eq}}$) which is determined as a function of $A_{\text{front}}^*$, an easily measurable and commonly used vegetation parameter in the field, (iv) the model can easily be calibrated for further experimental studies and an improved relationship for the equivalent porosity could be proposed to reproduce many conditions which are not possible to test due to the limitation of the laboratory facilities, and also to save both money and time, (v) the proposed coupling approach for the extended model for flexible vegetation enables the users to replace any solver of the model system with an alternative solver without having to adapt the other solver; however, more complicated models may possibly need much more computational power and are, particularly in the case of monolithic fully coupled fluid-vegetation models, more difficult and much less flexible/adaptive in practical applications.

The results of the comprehensive parameter study add two important new insights to the existing knowledge. First, it is necessary to consider the mutual interaction of the individual effects of the parameters on wave attenuation; ignoring these effects may result in incorrect and even contradictory conclusions. Second, for investigating the effect of different parameters on wave attenuation, the assumed conditions and applied approaches need to be taken into account. In fact, previous studies have shown that contradicting conclusions may arise from differences in the approaches used for testing and/or analysing the results (see examples in Section 4).

7 CONCLUDING REMARKS AND IMPLICATIONS FOR PRACTICAL APPLICATIONS

Overall, the study has successfully attempted (i) to develop and systematically validate a CFD model system for wave attenuation by both stiff and flexible vegetation under pure wave and wave-current conditions, (ii) to systematically identify the most relevant hydraulic and vegetation parameters affecting wave attenuation based on an extensive parameter study by applying the developed/validated model system, and (iii) to develop a new set of formulae for the prediction of wave attenuation by both stiff and flexible vegetation under pure wave and wave-current conditions.

The limitations of the proposed model system and of the results are systematically identified and recommendations to overcome them are made accordingly [Hadadpour, 2020]: (i) as the formula and the CFD model for flexible submerged vegetation under wave-current conditions are not yet validated due to the lack of appropriate data, well-designed laboratory experiments would be required for a final validation, (ii) as the relationship of equivalent porosity $n_{\text{eq}} = f(A_{\text{front}}^*)$ is crucial for the proposed porous media approach and as it is simply obtained by calibration using limited laboratory data, further data and studies would be needed. (iii) as density and buoyancy are kept constant in vertical direction, the effect of a non-uniform vertical biomass distribution on wave attenuation still needs to be investigated, (iv) as fluid and vegetation in the proposed model are not fully coupled, it is still unclear how and to which extent ‘monami’ could affect the accuracy of the results.

Based on the findings, the following aspects are recommended for practical implications:

- The proposed numerical approach is recommended as an appropriate tool to extend the range of conditions tested in the laboratory and assess the wave-attenuating capacity of vegetation for coastal protection purposes.
- Considering the effect of plant flexibility is crucial to avoid overestimation of wave energy dissipation in coastal protection projects, which may result in substantial damages.
- In most natural environments, particularly in tidal coasts, it is crucial to consider the effect of underlying currents on wave-attenuating capacity of vegetation and its potential as a natural solution for shore protection.
- A sufficient length of vegetation field is needed for each condition to maximise the effect of vegetation on wave height dissipation and hence the knowledge of this optimal meadow length is crucial for improving natural coastal defence planning.
- The proposed new prediction formulae for wave attenuation by stiff and flexible vegetation under both wave and wave-current conditions, which accounts for the most relevant parameters of vegetation and wave conditions, might represent an important step towards more reliable and well-validated formulae to help coastal communities to better assess coastal protection by different vegetation meadows.
- This is also particularly the case as these approaches can easily be adapted to also address the attenuation of ship-induced waves by both stiff and flexible vegetation which is commonly employed to mitigate bank erosion in waterways.
8 ACKNOWLEDGMENTS

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9 REFERENCES


SUMMARY

Recently, coastal protection has developed to one of the most crucial issues, resulting in a significant number of studies on the role of vegetation in shore protection. From the review of these studies, there is a general agreement that many complex physical processes are involved in the interaction of waves and currents with vegetation. Hence, there is still a need for further research of wave and/or current-vegetation interactions to improve the understanding of eco-hydraulic processes. This study therefore aims to improve the understanding of the highly complex wave-current-vegetation interaction, including a more precise and systematic identification of the most influential parameters on the wave attenuation.

For this purpose, a new porous media-based approach for the modelling of wave attenuation by stiff vegetation is applied using the Computational Fluid Dynamic (CFD) model, which is extended for flexible vegetation by considering the dynamic response of flexible vegetation subject to water waves/currents. The CFD model is systematically validated against laboratory tests for wave attenuation by both stiff and flexible vegetation. In addition, the wave damping effect of vegetation is investigated also for combined wave-current, which has been considered only in very few studies due to the high complexity of wave-current-vegetation interactions. A systematic parameter study using the extended model is performed for various vegetation and hydrodynamic conditions in order to better understand the relative contribution of the parameters and physical processes to wave attenuation by vegetation and thus, to provide a substantially larger dataset for the development of a new set of prediction formula for wave attenuation by vegetation under pure wave and wave-current conditions.

The results show that the proposed porous media modelling approach and the obtained new formulae perform relatively well for predicting wave attenuation by both stiff and flexible vegetation. Moreover, an improved insight not only into the effects of vegetation and hydraulic parameters but also into the mutual interaction of the individual parameters on wave attenuation is provided, highlighting the necessity to also consider the effects of these parameters in combination.

RESUME

Récemment, la protection des côtes est devenue l’une des questions les plus cruciales, ce qui a donné lieu à un nombre important d’études sur le rôle de la végétation dans la protection des côtes. D’après l’examen de ces études, il est généralement admis que de nombreux processus physiques complexes sont impliqués dans l’interaction des vagues et des courants avec la végétation. Par conséquent, il est encore nécessaire de poursuivre les recherches sur les interactions entre les vagues et/ou les courants et la végétation afin d’améliorer la compréhension des processus éco-hydrauliques. Cette étude vise donc à améliorer la compréhension de l’interaction très complexe entre les vagues, les courants et la végétation, y compris une identification plus précise et systématique des paramètres les plus influents sur l’atténuation des vagues.

Dans ce but, une nouvelle approche basée sur les milieux poreux pour la modélisation de l’atténuation des vagues par la végétation rigide est appliquée en utilisant le modèle CFD (Computational Fluid Dynamic), qui est étendu à la végétation flexible en considérant la réponse dynamique de la végétation flexible soumise aux

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1 The presented study is conducted within the author's doctoral studies at the Leichtweiß-Institute from October 2015 to April 2020. This article summarizes the main findings of the author's doctoral dissertation (Hadadpour, 2020). The main outcomes of this dissertation are prepared for publication in journal papers (Hadadpour et al., 2019, 2021; Hadadpour and Oumeraci, 2022).
Les résultats montrent que l'approche de modélisation des milieux poreux proposée et les nouvelles formules obtenues fonctionnent relativement bien pour prédire l'atténuation des vagues par la végétation rigide et flexible. De plus, une meilleure compréhension non seulement des effets de la végétation et des paramètres hydrauliques mais aussi de l'interaction mutuelle des paramètres individuels sur l'atténuation des vagues est fournie, soulignant la nécessité de considérer également les effets de ces paramètres en combinaison.

ZUSAMMENFASSUNG

In letzter Zeit hat sich der Küstenschutz zu einem der wichtigsten Themen entwickelt, was zu einer beträchtlichen Anzahl von Studien über die Rolle der Vegetation beim Küstenschutz geführt hat. Aus der Auswertung dieser Studien geht allgemein hervor, dass viele komplexe physikalische Prozesse an der Interaktion von Wellen und Strömungen mit der Vegetation beteiligt sind. Daher besteht noch immer Bedarf an weiteren Untersuchungen der Wechselwirkungen zwischen Wellen und/oder Strömungen und Vegetation, um das Verständnis der ökohydraulischen Prozesse zu verbessern. Diese Studie zielt daher darauf ab, das Verständnis der hochkomplexen Wechselwirkung zwischen Welle, Strömung und Vegetation zu verbessern, einschließlich einer genaueren und systematischen Identifizierung der einflussreichsten Parameter auf die Wellendämpfung.

Zu diesem Zweck wird ein neuer, auf porösen Medien basierender Ansatz für die Modellierung der Wellendämpfung durch steife Vegetation unter Verwendung des Computational Fluid Dynamic (CFD)-Modells angewandt, das für flexible Vegetation erweitert wird, indem die dynamische Reaktion flexibler Vegetation auf Wasserwellen/Strömungen berücksichtigt wird. Das CFD-Modell wird systematisch anhand von Labortests zur Wellendämpfung durch starre und flexible Vegetation validiert. Darüber hinaus wird die wellendämpfende Wirkung der Vegetation auch für die Kombination von Welle und Strömung untersucht, die aufgrund der hohen Komplexität der Wechselwirkungen zwischen Welle, Strömung und Vegetation bisher nur in sehr wenigen Studien berücksichtigt wurde. Eine systematische Parameterstudie unter Verwendung des erweiterten Modells wird für verschiedene Vegetations- und hydrodynamische Bedingungen durchgeführt, um den relativen Beitrag der Parameter und physikalischen Prozesse zur Wellendämpfung durch die Vegetation besser zu verstehen und somit einen wesentlich größeren Datensatz für die Entwicklung einer neuen Reihe von Vorhersageformeln für die Wellendämpfung durch die Vegetation unter reinen Wellen- und Wellenstrombedingungen bereitzustellen.

Die Ergebnisse zeigen, dass der vorgeschlagene Ansatz zur Modellierung poröser Medien und die erhaltenen neuen Formeln relativ gut für die Vorhersage der Wellendämpfung sowohl durch steife als auch durch flexible Vegetation geeignet sind. Darüber hinaus wird ein besserer Einblick nicht nur in die Auswirkungen der Vegetation und der hydraulischen Parameter, sondern auch in die gegenseitige Wechselwirkung der einzelnen Parameter auf die Wellendämpfung gewährt, was die Notwendigkeit unterstreicht, auch die Auswirkungen dieser Parameter in Kombination zu berücksichtigen.

RESUMEN

Recientemente, la protección de las costas se ha convertido en uno de los temas más cruciales, lo que ha dado lugar a un número importante de estudios sobre el papel de la vegetación en la protección de las costas. De la revisión de estos estudios se desprende que hay un acuerdo general en que en la interacción de las olas y las corrientes con la vegetación intervienen muchos procesos físicos complejos. Por lo tanto, sigue siendo necesario seguir investigando las interacciones entre las olas y/o las corrientes y la vegetación para mejorar la comprensión de los procesos ecohidráulicos. Por lo tanto, este estudio pretende mejorar la comprensión de la
complejísima interacción oleaje-corriente-vegetación, incluyendo una identificación más precisa y sistemática de los parámetros más influyentes en la atenuación del oleaje.

Para ello, se aplica un nuevo enfoque basado en medios porosos para la modelización de la atenuación del oleaje por parte de la vegetación rígida utilizando el modelo de Dinámica de Fluidos Computacional (CFD), que se amplía para la vegetación flexible considerando la respuesta dinámica de la vegetación flexible sometida a las olas/corrientes de agua. El modelo CFD se valida sistemáticamente frente a las pruebas de laboratorio para la atenuación de las olas por parte de la vegetación rígida y flexible. Además, el efecto de amortiguación del oleaje por parte de la vegetación se investiga también para la combinación oleaje-corriente, que sólo se ha considerado en muy pocos estudios debido a la gran complejidad de las interacciones oleaje-corriente-vegetación. Se realiza un estudio sistemático de parámetros utilizando el modelo ampliado para diversas condiciones de vegetación e hidrodinámicas con el fin de comprender mejor la contribución relativa de los parámetros y los procesos físicos a la atenuación del oleaje por la vegetación y, por tanto, proporcionar un conjunto de datos sustancialmente mayor para el desarrollo de un nuevo conjunto de fórmulas de predicción de la atenuación del oleaje por la vegetación en condiciones de oleaje puro y de corriente de oleaje.

Los resultados muestran que el enfoque de modelización de medios porosos propuesto y las nuevas fórmulas obtenidas funcionan relativamente bien para predecir la atenuación del oleaje por la vegetación, tanto rígida como flexible. Además, se proporciona una visión mejorada no sólo de los efectos de la vegetación y los parámetros hidráulicos, sino también de la interacción mutua de los parámetros individuales en la atenuación de las olas, destacando la necesidad de considerar también los efectos de estos parámetros en combinación.
INTRODUCTION

In Japan, many structures constructed during high economic growth period are now reaching the end of working life. In addition, typhoons, which are becoming larger and of which tracks are changing due to global warming, frequently causes external forces that exceed design conditions. For those reasons, the maintenance of public facilities is important due to the aging of structures and the increasing severity of disasters. On the other hand, productivity improvement in the construction field has also become an important issue because the working-age population is decreasing. In these regards, the utilisation of Information and Communication Technology (ICT) and 3-D data is expected to contribute to labour-saving and productivity improvement in construction work. The Ministry of Land, Infrastructure, Transport and Tourism (hereafter referred to as ‘MLIT’) is therefore working on an i-Construction policy to make the construction industry more attractive.

In ports, ICT and 3-D data are increasingly used for design, construction, and maintenance in many projects such as dredging, foundation work, main body work, and block installation work. For example, ICT is introduced in surveying and construction management, and 3-D data in design and maintenance of port facilities [National Institute for Land and Infrastructure Management, 2018]. However, that is not the case for wave-dissipating works because wave-dissipating blocks are installed randomly and in a complicated fashion.

Therefore, we have investigated the utilization of ICT and 3-D data in wave-dissipating works. This paper presents examples of maintenance methods for wave-dissipating works using 3-D data.

UAV SURVEYING ON WAVE-DISSIPATING WORKS

3-D surveying on wave-dissipating works using an Unmanned Aerial Vehicle (UAV) (hereafter referred to as ‘UAV surveying’) was carried out. The main purpose of the UAV surveying was to visually and quantitatively understand the condition of the wave-dissipating works. As the UAV surveying gives three-dimensional views of the wave dissipating works, it is possible to draw a cross-sectional profile at any location on it. Quantitative analysis gives the degree of deterioration by using the crown height, amount of subsidence, area of subsidence, volume of subsidence, etc.

One of the advantages of UAV surveying is it provides safer and swifter field work than in the conventional method (see Figure 2). This results in labour-saving. The UAV surveying of wave-dissipating works is conducted in the
following steps: ( i ) planning of field works including flight setting; ( ii ) installation and coordinate measurement of Ground Control Points (GCPs); ( iii ) continuous photographing by UAV; ( iv ) analysis of the GCP coordinates; ( v ) creation of point cloud data; ( vi ) making of cross-sectional profiles and composite images; and ( vii) conversion to Digital Surface Model (DSM). Among these steps, ( ii ) and ( iii ) are done in the field, while the rest are done on a tablet or PC.

Figure 1 shows the 3-D point cloud data of a 2.5 km-long breakwater A, surveying time of which at the site was about 4 hours. Figure 2 gives the schematic image of the conventional method for measuring the crown height of the wave-dissipating works. The measurement is made with a level staff by a pair of workers; one standing on the caisson and the another on the blocks. Usually, the measurement is conducted at places where subsidence is heavy. The time required for the measurement of the same breakwater by the conventional method would be about a week.

![3D data of breakwater A](image1)

**Figure 1: Example of 3-D data using UAV**

![Conventional surveying method in wave-dissipating works](image2)

**Figure 2: Conventional surveying method in wave-dissipating works**
3 EVALUATION OF DETERIORATION OF WAVE-DISSIPATING WORKS

6.1 Technical Guideline for Port Facilities Maintenance

The Japanese guideline [MLIT, 2021] specifies the general rules of maintenance through periodic inspection and diagnosis for port facilities. Table 1 shows the deterioration criteria of wave-dissipating works. The items to be inspected are: ‘movement, scattering and subsidence’, and ‘damage and cracks’. All of these are visually inspected.

<table>
<thead>
<tr>
<th>Target facilities</th>
<th>Inspection items</th>
<th>Inspection methods</th>
<th>Judgment criteria for deterioration degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caisson type breakwater</td>
<td>Movement Scattering Subsidence</td>
<td>Visual inspection •Deformation of crown, slope, shoulder, etc. of wave-dissipating works •Movement and scattering of wave-dissipating blocks</td>
<td>a. The cross-section of the wave-dissipating works was reduced by more than one layer thickness of block.</td>
</tr>
<tr>
<td></td>
<td>Damage Cracks</td>
<td>Visual inspection •Damage and cracks of wave-dissipating blocks •Number of broken blocks</td>
<td>b. The cross-section of the wave-dissipating works was reduced by less than one layer thickness of block.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c. Some wave-dissipating blocks had moved, scattered or subsided.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>d. No deformation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>e. More than 25 % of the blocks were damaged.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>f. Damages between a and c.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>g. Some wave-dissipating blocks were damaged.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>h. No damage.</td>
</tr>
</tbody>
</table>

Table 1: Judgment criteria for the degree of deterioration in wave-dissipating works (modified after MLIT (2021))

6.2 An Example of Deterioration Degree Judgment by 3-D Data

According to the criteria shown in Table 1, an evaluation method for the deterioration of wave-dissipating works using 3-D data was examined. In this paper, the inspection items focused on are the subsidence of wave-dissipating works and the damage to blocks.

For the subsidence of wave-dissipating works, the distance from the designed crown height to the observed height was calculated as the subsidence amount by using 3-D data. Figure 3 shows the result of the 3-D data analysis: observed (blue line) and designed (yellow line) crown heights are drawn in the longitudinal direction. The area enclosed by the two lines was calculated as the subsidence area (pink shaded area). Then, the average subsidence amount (red line) was calculated by dividing the subsidence area by the section length. This sequence of work was repeated for each section of the entire length.

Figure 3: Subsidence amount calculation
For damage to blocks, the number of broken blocks was visually counted using a composite image (orthoimage) and the 3-D data are as shown in Figure 4.

![Figure 4: Counting damaged blocks](image)

Table 2 shows an example of the evaluation on deterioration extent on a wave-dissipating works using the above mentioned method. The degree of deterioration (a, b, c and d) in wave-dissipating works is judged by applying the average subsidence amount and the number of damaged blocks to the criteria in Table 1. However, Table 1 does not provide specific values of criteria for subsidence and block damage, therefore a set of new judgment criteria is provided as shown in Table 3. While the conventional surveying method (Figure 2) can only provide the condition of certain sections, or a limited range of the wave-dissipating works, our method can continuously and precisely provide for the condition of the entire wave-dissipating works.

<table>
<thead>
<tr>
<th>Inspection items</th>
<th>Inspection results</th>
<th>Totalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidence</td>
<td>Section No.</td>
<td>a b c d</td>
</tr>
<tr>
<td>Damage</td>
<td></td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 ...</td>
<td>Count Ratio</td>
</tr>
<tr>
<td>Subsidence</td>
<td>b a c b b c b a a ... c</td>
<td>2 0.067 11 0.367 17 0.567 0 0.000 30 1</td>
</tr>
<tr>
<td>Damage</td>
<td>c b a c c c b c c ... b</td>
<td>1 0.033 7 0.233 19 0.633 3 0.100 30 1</td>
</tr>
</tbody>
</table>

Table 2: Example of the evaluation on deterioration extent on a wave-dissipating works using 3-D data

<table>
<thead>
<tr>
<th>Degree of deterioration</th>
<th>Subsidence amount $d_s$ ($l$: Half the length of two layers of blocks)</th>
<th>Number of damage blocks $n$ ($N$: Total number above the sea level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$l \leq d_s$</td>
<td>$N/4 \leq n$</td>
</tr>
<tr>
<td>b</td>
<td>$0.5 l \leq d_s &lt; l$</td>
<td>$N/8 \leq n &lt; N/4$</td>
</tr>
<tr>
<td>c</td>
<td>$0.1 l \leq d_s &lt; 0.5 l$</td>
<td>$1 \leq n &lt; N/8$</td>
</tr>
<tr>
<td>d</td>
<td>$d_s &lt; 0.1 l$</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: New judgment criteria for the degree of deterioration in wave-dissipating works
4 CALCULATION OF REPLENISHMENT QUANTITY

6.3 Calculation Method of Block Replenishment Quantity

When a wave-dissipating works has subsided due to wave action, blocks may be replenished as a maintenance project. In such cases, the shortage of blocks relative to the design quantity is generally calculated using the average cross-section method (Method 1). In Method 1, the replenishment area of each cross section is calculated by subtracting the existing cross-sectional area from the design cross section. Then, the replenishment volume is calculated by multiplying the average of the replenishment areas of the two adjacent cross sections by the section extension, and this is converted to the number of blocks. This process is repeated for each section. However, the longer the length of the wave-dissipating works, the more the number of the cross-sectional profiles, which results in an increase of time and effort required for calculation.

Therefore, a method for calculating the number of wave-dissipating blocks by using 3-D data (Method 2) was examined. Figure 5 shows the calculation image for Method 2. First, the volume of the existing wave-dissipating works was directly calculated by using 3-D data (Ve). Then, the replenishment volume (volume shortage) was obtained by subtracting Ve from the volume of the designed wave-dissipating works (Vd). Finally, the number of blocks required was calculated by converting for the replenishment volume.

6.4 Verification of the Method 2 for Replenishment Volume Calculation

The verification was conducted by calculating the replenishment volume at a section 30 m long using Method 1 and Method 2. The work time for each method was also measured.

In Method 1, cross-sectional profiles were created from 3-D data at intervals of 5 m (7 cross sections) and 15 m (3 cross sections) (Figure 6).
Then the replenishment area of each cross section was obtained as the difference between the existing and the design cross-sectional areas. The replenishment volume was calculated by multiplying the average of the replenishment areas of the two adjacent cross sections by the interval length (15 m and 5 m).

As explained in Figure 5, Method 2 provides the replenishment volume of the wave-dissipating works as the difference between the 3-D design data (the blue trapezoidal shape in Figure 7) and the existing data (the red area in Figure 7) [Noboru et al., 2018].

![Figure 7: Example of calculation of the replenishment volume by difference (Method 2)](image)

The results are shown in Table 4. The volume calculated and the time required for each case are compared as the ratio against the results of Method 1 with 3 cross sections (15 m intervals). The volumes calculated are larger in the order of Method 2, Method 1 with 7 cross sections, and Method 1 with 3 cross sections. This can be attributed to the fact that Method 2 reflects the unevenness of the blocks in detail, resulting in higher accuracy. As for the time required for Method 1, the calculation time is longer when the number of cross sections is larger. On the other hand, Method 2 enables the calculation of the existing volume in a shorter time than Method 1, and it is clear that the calculation time is significantly shorter if the design volume is obtained in advance.

<table>
<thead>
<tr>
<th>Calculation methods</th>
<th>Ratio of calculated volumes (%)</th>
<th>Ratio of time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1 3 cross sections</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Method 1 7 cross sections</td>
<td>101.6</td>
<td>200</td>
</tr>
<tr>
<td>Method 2</td>
<td>102.3</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Table 4: Calculation results of replenishment volume

Next, Method 2 was applied to a wave-dissipating works of 1.5 km long to measure calculation time. The site was divided into 15 sections of 100 m length and the replenishment volume of each section and time required for the calculation were measured. Figure 8 shows the results. The calculation time required for the entire length (1.5 km) was about 4 hours (about 15 minutes per section).

The accuracy of the 3-D data used is high as the data obtained by UAV surveying are corrected by GCPs. Therefore, the volume of the existing wave-dissipating works in Method 2 is considered to be
calculated accurately. However, as Method 2 precisely took into calculation the unevenness of the shape of the existing wave-dissipating works, the volume obtained by Method 2 may have some errors compared with the actual replenishment volume. The verification of its accuracy will be described in the next chapter.

5 ACCURACY VERIFICATION OF METHOD 2 FOR REPLENISHMENT VOLUME CALCULATION

The factors which affect the accuracy of the calculation of replenishment volume are considered to be surface irregularity, structure type and block size. In this chapter, the calculation accuracy of Method 2 is examined by focusing on the surface irregularity of a wave-dissipating works.

6.5 Verification Method

The verification was carried out using 1/70 model (numbers used in Figure 9 and Figure 10 are converted to actual size), in the following steps: (i) the volume of a prism with two trapezoidal bases which represents a wave-dissipating works (hereinafter referred to as the trapezoidal volume $V_t$) and the required number of blocks to fill in $V_t$ were obtained as shown in Figure 9; (ii) a trapezoidal-type wave-dissipating works was reproduced by piling up 156 mortar block models as shown in Figure 10; (iii) the point cloud data were obtained by 3-D hand scanner as shown in Figure 11 and converted to the actual size; (iv) Digital Surface Model (DSM) data were created from the point cloud data using analysis software; (v) the volume considering the unevenness of the wave-dissipating works was directly calculated using the DSM data (hereinafter referred to as the calculated volume $V_c$) as shown in Figure 12; (vi) the trapezoidal volume $V_t$ and the calculated volume $V_c$ were compared.

Figure 9: Specifications of wave-dissipating works

Volume of blocks : $v = 25.6 \text{ m}^3$ (64 t type)
Porosity : $p = 0.5$ (50 %)
Length of wave-dissipating works : 35 m
$V_t : 7,963 \text{ m}^3$
Required number of blocks : $\frac{V_t (1-p)}{v} = 156$ blocks

Figure 8: Examples of 3-D data and calculation results
In order to examine the effect of the difference in the reproducibility of unevenness on the calculated volume, 6 sets of lattice size of the DSM were set as shown in the upper row of Table 5.

<table>
<thead>
<tr>
<th>Lattice size of the DSM (cm)</th>
<th>5</th>
<th>10</th>
<th>14</th>
<th>20</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point density $D_s$ (number of point/m²)</td>
<td>400</td>
<td>100</td>
<td>51</td>
<td>25</td>
<td>11</td>
<td>4</td>
</tr>
</tbody>
</table>

Reproducibility of unevenness of wave-dissipating works

Table 5: Lattice size and point density of DSM
for analytical purposes. The point density $D_p$ in the lower row is described later. Figure 13 shows some examples of DSM data for each lattice size. The calculation was made 10 times for each set.

Figure 13: Examples of DSM data for each lattice size

6.6 The Effect of Lattice Size on the Calculated Volume in Wave-Dissipating Works

Figure 14 shows the results of the examination: lattice size of the DSM on the horizontal axis and the ratio of $V_c$ to $V_t$ on the vertical axis (hereafter referred to as the volume ratio). The volume ratios, tending to decrease as the lattice size increase, are less than 1 for all cases. This may be attributed to the effect of the unevenness of the surface as shown in Figure 15.

Figure 14: Relationship of volume ratio to lattice size of DSM

Figure 15: Schematic image of the surface of wave-dissipating works
6.7 A Formula for Replenishment Volume Calculation Considering Surface Irregularity

The coefficient that makes the calculated volume $V_c$ equal to the trapezoidal volume $V_t$ is $\alpha_1 (= V_t / V_c)$, and the relationship of $\alpha_1$ to the point density $D_p$ (number of point/m$^2$) is shown in Figure 16. Here, the point density $D_p$ is converted from the lattice size of DSM to the number of points per square meter (Figure 17), and the relationship between the lattice size and the point density $D_p$ is shown in Table 5. In Figure 16, the black cross marks indicate $\alpha_1$, and the red circles are the average value of $\alpha_1$ at each point density $D_p$. The coefficient $\alpha_1$ has a decreasing trend in the range of $4 \leq D_p < 50$ and is almost constant for $D_p \geq 50$. Therefore, the average value of $\alpha_1$ can be formulated as Equation (1).

$$\alpha_1 = \begin{cases} 1.16D_p^{0.013} & (4 \leq D_p < 50) \\ 1.10 & (D_p \geq 50) \end{cases}$$

![Figure 16: Relationship of $\alpha_1$ to the point density](image)

Figure 18 shows the schematic image of volume calculation of the wave-dissipating works after replenishment. The replenishment volume $V_r$ in a wave-dissipating works is calculated by the difference between the design volume $V_d$ and the existing volume $V_e$ obtained by Method 2 ($= V_c$). However, it was found that $V_c$ is affected by the surface irregularity of the wave-dissipating works. Therefore, the corrected volume $V'_e$, taking into account the effect by surface irregularity, can be formulated as Equation (2). This Equation (2) can calculate the number of blocks from 3-D data accurately and efficiently.

$V_e$ before verification $V_r = V_d - V_c$

$V_e'$ after verification $V'_r = V_c - \alpha_1 \times V_c$

![Figure 18: Volume calculation of the wave-dissipating works after replenishment](image)
\[ V_{r} = V_{d} - a_{1} \times V_{c} \]  

(2)

The remaining factors, which may affect the accuracy, such as the shape and size of the blocks and cross-sectional shape of the wave-dissipating works will be examined in the future.

6 MODELING OF WAVE-DISSIPATING WORKS

In recent years, Building/Construction Information Modelling, Management (BIM/CIM) has been introduced in Japan in order to improve the efficiency and the productivity of projects by sharing 3-D model information of structures at each phase of surveying, design, construction, and maintenance [Japan Federation of Construction Contractors, 2019]. A 3-D model of a target structure in BIM/CIM has the design and construction information (attribute information) assigned to each member of the structure. So far, this is not the case for wave-dissipating works. Individual blocks are not distinguished nor handled independently.

Therefore, a set of software that automatically arranges and installs the 3-D data of individual blocks on the data of an entire wave-dissipating works has been developed, aiming to sophisticate the design, construction, and maintenance of wave-dissipating works. The following is a brief explanation.

6.8 Creation Method of 3-D Model of Wave-Dissipating Works

A 3-D model of wave-dissipating works can be created automatically using Software A and Software B. Importantly, the model is produced as a solid model and provides attributable information on each block.

Software A automatically arranges a 3-D model of a block to match the responding point cloud data of the current condition. By using this, the existing condition of wave dissipating works can be faithfully reproduced, as is the case for completed conditions after replenishment. For example, a model block can be placed to match the exact place and posture by selecting and specifying a specific part in the point cloud data as a reference (Figure 19). Figure 20 shows an example of 3-D modelling of a wave-dissipating works with Software A. The minimum time for automatic placement is about one minute per block. The accuracy of the placement is generally within the gap of 3% of the block height between the point cloud data and the surface of the model.

Software B can create a model of randomly installed wave-dissipating works by free-falling 3-D models of individual blocks, as shown in Figure 21. Modelling time is usually within one hour (generally for 100 blocks). It is also possible to place new block models on the imported 3-D current data. Therefore, Software B can be expected to be used for construction planning in new and replenishment projects for wave-dissipating works.

![Figure 19: Placement of the model block in point cloud data](image)
6.9 Application of Modelling Data to Installation and Maintenance of Wave-Dissipating Works

In the modelling of wave-dissipating works by Software A and Software B, models are reproduced; posture can be obtained. Using these data, it will be possible to sophisticate the construction and maintenance of wave-dissipating works.

In construction, block installation is conducted by the crane operator following instructions given by divers, and this is unsafe and time consuming. With the 3-D modelling, the crane operation becomes safer and more efficient as the operator can check on the management screen for the target position (centre of gravity) and direction of each block, as shown in Figure 22.2.

In maintenance, the modelling data on the completion conditions of a wave-dissipating works include information on the initial condition of each block. Comparison before and after a disaster as well as age deterioration can be quantified. In the case of modelling the existing conditions, it is possible to faithfully...
reproduce the wave-dissipating works at the site. This allows a detailed installation plan for the blocks to be replenished. Furthermore, the modelling data on the blocks can provide use for BIM/CIM in a replenishment project of the wave-dissipating works.

7 CONCLUSIONS

In this study, labour-saving and efficiency improvement by application of 3-D data was studied, mainly on maintenance of wave-dissipating works.

The results are as follows:

- UAV surveying enables safer and swifter field work than the conventional method, resulting in more efficient and labour-saving evaluation of the current condition of wave-dissipating works;
- A method to accurately evaluate the subsidence of wave-dissipating works and the damage conditions of blocks by determining the deterioration degree using 3-D data is presented;
- A method for calculating the replenishment volume of blocks using 3-D data is presented. This was found to be faster and more efficient than the conventional method. Coefficients and equations for more accurate calculations were also proposed based on the results of the verification;
- A method for modelling individual blocks in wave-dissipating works was presented. With the model, it is possible to faithfully reproduce the current conditions and simulate the installation of new blocks to enable more efficient and sophisticated maintenance of the wave-dissipating works.

The authors believe that the results obtained in this paper are an important step forward for the sophistication of maintenance technology in wave-dissipating works. While this paper mainly focused on the wave dissipating works of caisson type breakwaters, the technology is easily applicable to other types of breakwaters such as sloping breakwaters which are widely used in many countries. Some issues remain, however, such as the effects of the structure type, and the shape and size of the block on the number of blocks to be replenished. Also the modelling of individual blocks and its applicability need to be further studied. The authors will continue their technical studies to improve the reliability of the methods presented in this paper.

8 REFERENCES


SUMMARY

This paper presents some examples of 3-D data application obtained by aerial surveying to the maintenance of wave-dissipating works, aimed at labor saving and productivity improvement. The results are as follows: ( i ) 3-D surveying of wave dissipating works using UAV enables safer and
swifter field work, as well as labour-saving compared to the conventional method; (ii) determining the degree of deterioration using 3-D data gives more accurate and efficient evaluations of wave dissipating works; (iii) a newly proposed calculation method of the replenishment number of wave-dissipating blocks (concrete armour units) by using 3-D data is found to be quicker and more efficient than the conventional method. In addition, since Building/Construction Information Modelling, Management (in Japan, called BIM/CIM) will be introduced to the construction of wave-dissipating works in the near future, a modelling method for individual wave-dissipating blocks (Tetrapods) is studied. By converting point cloud data to a solid model, it is possible to faithfully reproduce individual Tetrapods, and to simulate the place and direction of any new blocks to be installed. This enables more efficient and sophisticated maintenance in wave-dissipating works.

RESUME

Cet article présente quelques exemples d’application de données 3D obtenues par levé aérien à la maintenance des ouvrages de dissipation des vagues, dans le but d’économiser de la main-d’œuvre et d’améliorer la productivité. Les résultats sont les suivants : (i) l’arpentage 3D des ouvrages de dissipation des vagues à l’aide d’un drone permet un travail sur le terrain plus sûr et plus rapide, ainsi qu’une économie de main-d’œuvre par rapport à la méthode conventionnelle ; (ii) la détermination du degré de détérioration à l’aide de données 3D donne des évaluations plus précises et plus efficaces des ouvrages de dissipation des vagues ; (iii) une méthode de calcul nouvellement proposée du nombre de réapprovisionnement des blocs de dissipation des vagues (unités de blindage en béton) en utilisant des données 3D s’avère plus rapide et plus efficace que la méthode conventionnelle. En outre, étant donné que la modélisation et la gestion de l’information du bâtiment et de la construction (appelée BIM/CIM au Japon) seront introduites dans la construction des ouvrages de dissipation des vagues dans un avenir proche, une méthode de modélisation des blocs individuels de dissipation des vagues (tétrapodes) est étudiée. En convertissant les données des nuages de points en un modèle solide, il est possible de reproduire fidèlement les tétrapodes individuels et de simuler l’emplacement et la direction de tout nouveau bloc à installer. Cela permet une maintenance plus efficace et plus sophistiquée des ouvrages de dissipation des vagues.

ZUSAMMENFASSUNG

RESUMEN

Este artículo presenta algunos ejemplos de aplicación de datos tridimensionales obtenidos mediante topografía aérea al mantenimiento de obras de disipación de oleaje, con el fin de ahorrar mano de obra y mejorar la productividad. Los resultados son los siguientes: (i) la medición tridimensional de las obras de disipación de oleaje mediante UAV permite un trabajo de campo más seguro y rápido, así como un ahorro de mano de obra en comparación con el método convencional; (ii) la determinación del grado de deterioro mediante datos tridimensionales da lugar a evaluaciones más precisas y eficientes de las obras de disipación de oleaje; (iii) un método de cálculo recientemente propuesto del número de reposición de los bloques de disipación de oleaje (unidades de blindaje de hormigón) mediante el uso de datos tridimensionales resulta más rápido y eficiente que el método convencional. Además, dado que en un futuro próximo se introducirá en la construcción de obras de disipación de olas la gestión de la información sobre edificios/construcción (en Japón, denominada BIM/CIM), se estudia un método de modelado para bloques individuales de disipación de olas (tetrápodos). Al convertir los datos de la nube de puntos en un modelo sólido, es posible reproducir fielmente los Tetrápodos individuales, y simular el lugar y la dirección de los nuevos bloques que se instalen. Esto permite un mantenimiento más eficaz y sofisticado en las obras de disipación de oleaje.
1 INTRODUCTION

Seaports play an important role as hubs in the transhipment of goods and are an important driver of the economy and employment in the respective regions. Due to their location on the coast, they are particularly affected by the impending sea level rise due to climate change. Their functionality is also threatened by other consequences of climate change, such as the increase in extreme weather events. To ensure that seaports are equipped to meet both economic and environmental demands in the future, their vulnerability to climate change must be analysed at an early stage and measures to increase their resilience must be taken into account in port management.

In 2020, the PIANC Working Group 178 published the guideline ‘Climate Change Adaptation Planning for Ports and Inland Waterways’ [PIANC, 2020]. The guideline contains recommendations for the preparation of an adaptation strategy for ports and waterways in a four-stage process, whereby the relevant stakeholders are involved in each stage. The four stages cover the following:

1. Context and objectives
2. Climate information
3. Vulnerabilities and risks
4. Adaptation options

This paper presents the application of the PIANC guideline to German seaports, which was carried out as part of the project PortKLIMA ‘Development and Pilot Implementation of Educational Modules for Integrating Climate Change Adaptation into the Planning, Construction and Operation of Seaports in Germany’. A total of seven German seaports respectively their management organisations were involved in the project (Figure 1). As part of the project, interviews were conducted with the involved port management organisations in order to assess how the seaports involved are currently affected by extreme weather events and whether climate change adaptation measures are already in place.
2 RISKS AND OPPORTUNITIES RESULTING FROM CLIMATE CHANGE FOR GERMAN SEAPORTS

The vulnerability of seaports to climate change is manifold. Figure 2 shows an overview of relevant climate parameters and their effects on the different areas of seaports identified within the framework of the PIANC guideline. The current impact on the German seaports involved in the project PortKLIMA is shown in the boxes. It can be assumed that the current impact will increase in the future. Therefore, the systematic documentation of current impacts is a good starting point for deriving adaptation measures. Nevertheless, further impacts may occur in the future. However, it is important to notice that the cause is not only to be found in the climate system, as human interventions, such as deepening of fairways or an increase in ship sizes, can also be the cause of increasing challenges. If weather-related damage occurs, it may also be caused by material fatigue or lack of maintenance rather than the immediate extreme weather event.

Due to their location, seaports are particularly exposed to the effects of high water levels and strong winds. High water levels are already today becoming a problem for ports when the quay levels are only slightly above the mean high water level. Such quays are protected from flooding by walls located on the quays. Cargo handling in the port can only take place at certain wind strengths. Damage as a result of storm events, such as damaged roofs, is not unusual. In the past, there have also been isolated cases of overturned empty containers. The increase in ship sizes has increased their windage area. The challenges to be mentioned in relation to strong winds and ship sizes are the mooring of ships with partly increased use of tugs, scour damage due to bow thruster and occasionally ships that have broken loose, as well as ships that cannot enter narrow port entrances in extreme situations. In a few cases, unusual strong wind events were observed. These include long-lasting strong wind events in summer and storm events from an atypical direction.

The occurrence of hot spells has different effects on seaports. Especially for employees working in non-air-conditioned areas, high air temperatures are problematic. For older workers in particular, the high temperatures in the summers of 2018 and 2019 were a major challenge. Due to the high workload, there were also occasional failures of air conditioning systems in vehicles, which could be counteracted by switching them off during the night. In some ports, high temperatures caused damage to pavements (asphalt) and to track systems or impaired the operation of movable steel bridges. Furthermore, some work cannot be carried out at high temperatures.

Heavy precipitation events have hardly caused any problems in the ports. However, the handling of moisture-sensitive goods is restricted during precipitation. Storm water can often drain off well via the terminal drainage or the quay edge. So far, flooding has only occurred locally and for short periods. Gravelled areas may have to be prepared more frequently to prevent puddles from forming.
The future handling of storm water run-off from the terminal areas needs to be discussed in order to avoid critical water quality situations in the receiving waters when water temperatures rise and thus oxygen concentrations decrease. There is also the question of the capacity of the receiving waters in the event of rising sea levels.

In the past, a lack of precipitation affected the ports in different ways. Due to the resulting low water levels on the Rhine, a shift of freight flows to the railways could be observed, which led to a shortage of rail wagons, but also to a redistribution of goods to other port locations. Water levels that are too low also pose the risk of falling below the design water levels at the quays, so that the affected quays had to be closed for cargo handling.

<table>
<thead>
<tr>
<th>Navigation zone</th>
<th>Protection infrastructure</th>
<th>Maneuver area and berthing</th>
<th>Load/unload area</th>
<th>Port equipment</th>
<th>Storage</th>
<th>Processing</th>
<th>Hinterland connections</th>
</tr>
</thead>
</table>

The hinterland connections by ship, rail or truck are essential for maintaining the flow of goods. In the past, they were disrupted by low water levels and rail line failures due to storm damage or embankment fires as a result of extreme weather events.

Sediment transport or management in ports depends on a variety of factors. Both positive and negative effects on sediment management have been observed by affected ports, without being able to prove the exact causes in detail. Rising water temperatures and low oxygen concentrations may in future further limit the days on which sediment management measures such as dredging are permitted.

Locally, salt spray occurred within two years in a row. As a result, there have been problems with the power supply and the failure of overhead lines on railway tracks in the affected region. The event is actually considered to occur rarely.

In some ports, a change in freight flows due to extreme weather events could be observed. In addition to a diversion of goods as a result of low water, these include timber imports as a result of storm damage and grain exports or feed imports as a result of extreme drought. The changes in the flow of goods have so far not been negative for the ports for the most part, but not necessarily positive either.

Overall, the current impact on the ports involved is not to be classified as exceptional compared to historical conditions. However, the first challenges related to changing climatic conditions are becoming apparent.

In the final workshop of the PortKLIMA project, after the expected future regional climatic changes had been presented, the participants were asked for their personal assessment of the greatest future direct impact on the respective port (Figure 3). According to this, the greatest direct impact is the height of storm surge water levels, followed by the rise in mean sea level, the increase in heavy rain and severe weather events, extreme heat periods and storms.

Figure 2: Climate parameters and possible impacts on a seaport [PIANC, 2020]. The impacts highlighted in the boxes have already been observed in the German seaports participating in the project PortKLIMA.

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Even if the negative consequences of climate change outweigh the positive ones, climate change will have positive effects. For example, it is expected that ice and snow will occur less frequently in winter due to increased mean air temperatures. Rising sea levels will also increase water depths in waterways and harbours. A possible competitive advantage may arise from a port being better prepared than other locations to meet the challenges. Opportunities may also arise from climate change-related changes in freight flows.

![Figure 3: Result of the survey conducted during the final workshop regarding the greatest direct impacts expected for the port in the future (multiple-choice question, 22 participants)](image)

### 3 RELEVANT ASSET SERVICE LIVES AND THEIR SIGNIFICANCE FOR ADAPTATION MEASURES

For the development of an adaptation strategy, the planning horizon should take into account the service life of assets and the extent of change in relevant climate parameters and processes in relation to the service life of the assets. Table 1 shows an overview of average economic service lives of assets in seaports.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Average economic service life [Years]</th>
</tr>
</thead>
</table>
| Terminal- and port superstructure | Container bridge: 20\(^1\), 15\(^2\)  
                                    | Mobile crane: 15\(^1\)  
                                    | Straddle carrier: 6\(^3\), 5-10\(^1\)  
                                    | RoRo ramp: 15\(^3\)  
                                    | Warehouse: 25\(^3\), 40\(^1\); concrete: 25\(^2\); lightweight: 10\(^2\) |
| Pavement                       | Asphalt: 10-15\(^1\); concrete: 20\(^1\);  
                                    | Roads/surface pavements: 15\(^2\) |
| Railway track                  | According to legal requirements: 25\(^2\); other: 12\(^2\) |
| Drainage                       | Drainage: 33\(^3\) |
| Quay wall                      | Concrete: 40\(^3\); steel: 25\(^3\)  
                                    | Sheet piling: 50\(^3\), 20\(^2\); open berth: 50-100\(^1\);  
                                    | Rubber fender: 10\(^3\), 10-20\(^1\) |
| Flood protection structure     | >100\(^1\) |
| Breakwater                     | 50\(^3\), 100\(^1\) |
| Dolphin                        | 20\(^2\) |
| Pontoon                        | Concrete: 30\(^2\); metal/ steel: 30\(^2\) |

\(^1\) Thoresen (2010)  
\(^2\) Bundesfinanzministerium (2020)  
\(^3\) United Nations Conference on Trade and Development (1985)

Table 1: Average economic service life of assets in seaports. Actual service lives of individual assets depend on individual asset conditions and use and can therefore extend beyond the average economic service life.
For assets with short service lives or measures with short reaction times, it is generally easier to consider climate change impacts in planning. Measures can be implemented when a clear trend emerges and assets or equipment need to be renewed regardless of climate change. However, weather-related downtime and damage can already occur as a result of extreme weather. Therefore, if the potential damage is high, adaptation measures may already be appropriate for assets with short service lives. Terminals for special industries also have the advantage that they often have short service lives of up to 30 years, as the assets have to be adapted more frequently to changing economic and technical requirements. However, especially for assets with long service lives or long reaction times, the effects of climate change need to be considered at an early stage. If the potential damage is low, risks can be accepted. A possible decision matrix for evaluating the need for adaptation measures is shown in Table 2. At present large investments solely for the purpose of adaptation are generally not made for economic reasons.

<table>
<thead>
<tr>
<th>Service life/ reaction time</th>
<th>Potential damage</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>Ad-hoc measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>Accept risks</td>
<td>Take preventive action early</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Decision matrix to assess the need for adaptation measures according to Norpoth et al. (2020)

The participants of the final workshop were asked about their personal assessment of an extraordinary need for adaptation in their area of responsibility (Figure 4). Approximately half of the participants see an extraordinary need for adaptation or none at all.

4 REGIONAL IMPACTS OF CLIMATE CHANGE

After identifying relevant assets, port-related activities and related time horizons, as well as relevant climate parameters and processes, climatic changes for the recent past as well as for the future are determined. An overview of climatic changes for the North German coast is presented below, separated into meteorological (Table 3) and oceanographic (Table 4) parameters.

Extreme conditions are of particular interest for the dimensioning of assets and restrictions in operation. In this context, annualities are often used in planning, which are determined on the basis of probability or distribution functions and extreme values determined from hydrographs, e.g. annual maximum. In contrast, climate models are often used to investigate the change of certain threshold values (e.g. annual 98th percentile) for climatically relevant time horizons without considering the effects on the annuality. Especially since reliable statements about the change in annualities of particularly rare extreme events require extensive ensembles, and their changes cannot be inferred across-the-board from change signals of less
rare extreme events, even in the context of climate change [Lang and Mikołajewicz, 2020]. Thus, in addition to uncertainties in climate projections, there is another source of uncertainty as a result of the required transfer of climate projection results to relevant design parameters, which cannot be quantified in more detail or minimised substantially based on the available information.

In the long term, seaports will be affected primarily by the influence of sea level rise on the frequency of extreme water levels. The extent of the impairment depends not only on future greenhouse gas emissions, but also on the elevation of port areas. Depending on the scenario, by the end of the century a mean sea level rise of at least 0.4 m can be expected, which can also reach around 1.0 m or more if extreme changes occur (see Table 4). Beyond 2100, sea level rise of about 1.0 m is expected even with strong climate action [IPCC, 2019]. The effects of sea level rise on tidal dynamics are subject to uncertainties i.e. due to the future evolution of bathymetry associated with sea level rise [Winkel et al., 2020]. Overall, the influence on characteristics of high and low tides in German seaports is estimated to be small [Rasquin et al., 2020]. The same is true for the influence of mean sea level rise on wind surge (cf. Seiffert et al. (2014), Arns et al. (2017), Gräwe and Burchard (2012)) and wave parameters [Groll et al., 2014; Mai and Zimmermann, 2004]. Nevertheless, a rather small and negligible increase in terms of absolute height, also due to existing uncertainties, may have a more significant impact on the recurrence interval of an extreme water level event, so that, if necessary, the influence of tide and wind surge should be considered in the context of change in annuality.

In addition, increasing air temperatures and related events such as prolonged periods of heat and drought, extreme precipitation events, and rising water temperatures are to be expected [IPCC, 2021]. Annual maximum air temperature is expected to increase more than mean air temperature [IPCC, 2021]. Reliable statements for changes in design precipitation values based on the KOSTRA Heavy Rain Atlas are difficult due to the large model resolution required [Rauthe et al., 2020]. The Clausius-Clapeyron relationship appears to be a good benchmark to estimate the change in future extreme precipitation, but other dynamic factors, such as tracks of extratropical storms, also play a role [Lehmann et al., 2015]. Using the Clausius-Clapeyron relationship, it is possible to infer the increase in maximum air water vapour content with an increase in air temperature. There is also evidence of a disproportionate increase in convective heavy precipitation compared to the Clausius-Clapeyron relationship, although this weakens with increasing air temperature (from about 20° C) [Berg et al., 2013] and is therefore less relevant for summer heavy precipitation with the potential for particularly high precipitation intensities. As an alternative to the Clausius-Clapeyron relationship, an orientation towards the tolerance ranges according to KOSTRA [Junghänel et al., 2017], i.e. depending on the annuality +10 % (T ≤ 5a), +15 % (T ≤ 50a), or +20 % (T ≤ 100a), can be recommended.

Future changes in mean sea level and air temperature show robust change signals with more or less increase depending on the climate scenario, thus are mainly subject to scenario uncertainty. Future changes in storm climate and mean precipitation characteristics show less robust change signals. They are characterized by model uncertainty - the influence of the driving climate model - and are subject to stronger natural variability, i.e. their climate change signals often do not stand out as clearly from the natural background variability [DWD, 2020; Helmholtz-Zentrum Hereon, 2021a; de Winter et al., 2013; Ganske, 2019]. Uncertainties in the future wind climate inevitably affect statements about the future development of wind surge and sea state.
<table>
<thead>
<tr>
<th>Climate parameter</th>
<th>Historic change</th>
<th>Future change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average air temperature</td>
<td>+0.8°C (year), significant change(^1)</td>
<td>+1.0 to +5.1°C (year)(^2)</td>
</tr>
<tr>
<td>Hot days (Tmax ≥ 30 °C)</td>
<td>+2 days (year), no significant change(^1)</td>
<td>+0 to +30 days (year)(^2)</td>
</tr>
<tr>
<td>Ice days (Tmax &lt; 0°C)</td>
<td>-7 to -5 days (year), no significant change(^1)</td>
<td>-37 to -3 days (year)(^2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Despite decrease, potential for cold winters increases(^3)</td>
</tr>
<tr>
<td>Mean precipitation</td>
<td>+8 % (winter/ summer), no significant change(^1)</td>
<td>-46 to +56 % (summer), +3 to +42 % (winter)(^2)</td>
</tr>
<tr>
<td>Heavy rainfall days (≥ 20 mm)</td>
<td>No change(^1)</td>
<td>0 to +5 days (year)(^2)</td>
</tr>
<tr>
<td>Mean wind speed</td>
<td>+2 % (year), +6 % (winter), significant change(^1)</td>
<td>Mid-century: -3 to +4 % (year), -5 to +7 % (winter)(^6)</td>
</tr>
<tr>
<td></td>
<td>Shows decadal variability</td>
<td>End-century: -4 to +7 % (year), -8 to +14 % (winter)(^2)</td>
</tr>
<tr>
<td>Storm intensity vmax at 10 m height</td>
<td>+1 % (year), +5 % (winter), no significant change(^1)</td>
<td>Mid-century: -2 to +5 % (year), -4 to +11 % (winter)(^6)</td>
</tr>
<tr>
<td></td>
<td>Shows decadal variability</td>
<td>End-century: -4 to +4 % (year), -8 to +10 % (winter)(^2)</td>
</tr>
<tr>
<td>Storm days (vmax &gt; 62 km/h)</td>
<td>+3 days (year), +3 days (winter), no significant change(^1)</td>
<td>Mid-century: -7 to +13 days (year), -4 to +7 days (winter)(^6)</td>
</tr>
<tr>
<td></td>
<td>Shows decadal variability</td>
<td>End-century: -8 to +14 days (year), -8 to +10 days (winter)(^2)</td>
</tr>
<tr>
<td>Wind direction</td>
<td>N. s.</td>
<td>More frequent winds from westerly directions possible(^7)</td>
</tr>
<tr>
<td>Severe weather risk</td>
<td>No statement possible due to available data(^8)</td>
<td>No significant change for the North German coast(^9)</td>
</tr>
</tbody>
</table>

\(^1\) 1986-2015 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021b)
\(^2\) 2071-2100 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021a)
\(^3\) Dethloff et al. (2018)
\(^4\) Becker et al. (2016); \(^5\) Lehmann et al. (2015)
\(^6\) 2036-2065 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021a)
\(^7\) de Winter et al. (2013), Gaslikova et al. (2013), Dreier et al. (2015), Ganske (2019)
\(^8\) Kunz et al. (2017); \(^9\) Půčík et al. (2017)

Table 3: Observed and possible future change of meteorological climate parameters in northern Germany
Table 4: Observed and projected future change in hydrological and oceanographic climate parameters in northern Germany. SLR: Sea level rise
5 VULNERABILITY AND RISK FOR SEAPORTS IN GERMANY

Based on expected changes of relevant climate parameters and processes at the German coast, a general assessment of exposure and vulnerability for different assets and activities in German seaports was carried out. The assessment is done qualitatively based on the PIANC guideline [PIANC, 2020]. Table 5 shows an example of the result of the overarching vulnerability analysis based on Level 3 of the PIANC guideline for a moderate greenhouse gas scenario (RCP4.5), which must currently be considered a realistic scenario [Hausfather and Peters, 2020].

![Table 5: Exemplary result of an overarching vulnerability analysis for seaports in Germany based on PIANC (2020) for the near and distant future of the ‘moderate’ scenario (RCP4.5).]

The analysis shows that for the scenario in question, it is above all the rise in air temperature and mean sea level as well as heavy rainfall that result in an increase in the vulnerability of seaports in Germany. However, statements are partly dependent on individual conditions on site (freeboard, significant wave height, geographical orientation of berth). In principle, the analysis should be differentiated according to various climate scenarios.

<table>
<thead>
<tr>
<th>Examples of relevant climate parameters and processes</th>
<th>Examples of critical assets, operations, systems</th>
<th>Compared to historical data, how does exposure change due to potential climate hazards within the planning horizon?</th>
<th>Considering relevant thresholds and existing adaptive capacity, how is vulnerability likely to change?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access to the berth – fairway</td>
<td>Extreme heat</td>
<td>Significant increase</td>
<td>Significant increase</td>
</tr>
<tr>
<td></td>
<td>Sea level rise</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Storm intensity</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>Sea state</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td></td>
<td>Heavy rain</td>
<td>Significant decrease</td>
<td>Significant decrease</td>
</tr>
<tr>
<td>Locks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other berthing facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mooring facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mooring, loading and unloading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handling equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood protection facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage areas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warehouses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Railway tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drainage systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Depending on development of sediment transport
2 Depending on existing freeboard/ the elevation/ the topography
3 Depending on asset and service life
4 Depending on pavement (asphalt, concrete, paving) and service life
Schröder et al. (2013) questioned 10 ports on the Baltic Sea coast when a sea-level rise would have problematic effects for the respective port. 20% of respondents indicated a sea level rise of 40-59 cm and 90% a rise of 80-99 cm as problematic. If the results of the study are applied to the entire German coast, the majority of ports would only be significantly affected by a sea-level rise such as that expected under the 'business as usual' scenario at the end of this century.

With regard to the influence of extremely high temperatures, in addition to the stress on employees in non-air-conditioned rooms, an increased vulnerability of or increased need for air-conditioning must be mentioned. Furthermore, materials can also be affected by extreme temperatures. In addition to asphalt pavements, which can be adapted during replacement, depending on their service life, sun-exposed steel components and electronic switching elements should be considered. Heavy rainfall primarily affects drainage systems and, if they are overloaded, areas affected by flooding as well as buildings, and leads to impairments in handling activities.

As part of the development of an adaptation strategy, the probability of being affected and the degree of risk for the port must be assessed. Compared to identification of relevant climate parameters and processes according to Storch et al. (2018), this is the area with the greatest potential for uncertainty regarding the effects of climate change on seaports. However, from the current perspective, this potential for uncertainty cannot be significantly reduced due to the diverse factors influencing future impacts.

In the next step, adaptation measures can possibly already be derived directly from the vulnerability analysis. However, more detailed risk assessments are also possible. Risk analysis considers the impact of a potential climate hazard and the probability of its occurrence or classification. Figure 5 shows the result of such an exemplary assessment for the consequences of sea-level rise. Ultimately, only areas affected by flooding have at least moderate significance for the functionality of the port are subject to a high risk for the corresponding climate hazard or scenario.

![Figure 5: Left: Flood hazard map of a harbour area for a climate hazard (storm surge, including sea level rise). Right: Risk resulting from superposition of probability of climate hazard and impact of climate hazard. [Baumgärtner, 2020].](image)

Table 6 shows operational thresholds in respect of handling and berthing operations, above which operations in seaports are affected. Not all facilities have to be affected to the same extent. Ultimately, both mooring system (winch, mooring line, bollards) and cargo handling equipment would have to be adapted for increased adaptation. Apart from that, for safety reasons, it is advisable to stop activities in the port above a certain wind speed. It can therefore be assumed that operational threshold values for wind speeds cannot be significantly increased due to technical measures, but that activities must be stopped at certain wind speeds, as has been the case up to now. Thus, adaptation measures are limited to minimise the extent of storm-related damage or accidents.
To what extent is the topic of climate change adaptation already taken into account in your organisational policy?

![Bar chart showing the distribution of responses]

**Table 6: Critical wind speed thresholds for seaport operations (Gaythwaite (2004), modified).**

<table>
<thead>
<tr>
<th>Beaufort scale/ description</th>
<th>Wind speed [m/s]**</th>
<th>Effect on operations**</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Strong breeze</td>
<td>11.5 – 14.0</td>
<td>Berthing limit</td>
</tr>
<tr>
<td>7 Near gale</td>
<td>14.5 – 17.0</td>
<td>Tugboat limit</td>
</tr>
<tr>
<td>8 Fresh gale</td>
<td>17.5 – 20.5</td>
<td>Ferry operations cease</td>
</tr>
<tr>
<td>9 Strong gale</td>
<td>21.0 – 24.0</td>
<td>Emergency mooring lines</td>
</tr>
<tr>
<td>10 Whole gale</td>
<td>24.5 – 28.5</td>
<td>Large vessels put to sea</td>
</tr>
<tr>
<td>11 Storm</td>
<td>29.0 – 32.5</td>
<td>Facilities secured, cranes lashed etc.</td>
</tr>
<tr>
<td>12 Hurricane</td>
<td>≥ 33.0</td>
<td></td>
</tr>
</tbody>
</table>

* Round to 0.5 m/s
** Due to wind, in exposed locations wave action may lead to greater restrictions

The North German Climate Monitor (Helmholtz Centre Hereon 2021b) indicates an average of about 40 storm days per year (maximum wind speed ≥ 8 Beaufort) for the North German coast in the period 1961-1990. Climate projections show, depending on the model run, a possible increase or decrease in the number of storm days of +14 to -8 for the end of the 21st century [Helmholtz-Zentrum Hereon, 2021a]. Accordingly, an increase in the frequency of wind-related operational restrictions in seaports in Germany is not necessarily given.

### 6 ADAPTATION OF SEAPORTS IN GERMANY TO CLIMATE CHANGE

Adaptation to climate change has so far been taken into account to varying degrees, from very high to very low, in the participating port management companies (Figure 6). In addition, the majority of participants estimate that there is up to five years left to sufficiently integrate the topic of climate change adaptation into the company respectively the area of responsibility (Figure 7).
In principle, the portfolios presented in the PIANC guideline [PIANC, 2020] provide a comprehensive catalogue of measures to significantly increase the resilience of ports to climate change. Adaptation options in the PIANC guideline are divided into physical, social and institutional measures. Physical measures in particular require economic investments, which can be significant depending on the expected impacts. Social and institutional measures usually require smaller investments. The time required for the implementation of measures is strongly dependent on available human and financial resources and can be small to considerable depending on the measure.

At present, the most important measure is the implementation of an adaptation strategy. The importance of this lies above all in dealing with the future impact of climate change at an early stage, so that measures can already be planned preventively and implemented with the greatest possible economic efficiency. Even if the climatic changes and the associated effects will only become clearer in the future, the probability of extreme weather events such as heat waves is already increased today [Vautard et al., 2020]. Furthermore, it makes sense to integrate the consequences of climate change at an early stage, especially in new construction and planning projects with a long time horizon and to set up monitoring programmes in order to build up a supportive data basis on one’s own affectedness for future decisions. In other words, it is recommended that climate change adaptation is considered today, even if in principle there is time for adaptation and the current need for action tends to be manageable. The timeframe of up to five years indicated by the majority of participants in the final workshop of the PortKLIMA project for the appropriate integration of climate change adaptation therefore seems realistic. Whether there is already a need for specific action with regard to physical measures at present or in the near future depends on the individual circumstances of the individual ports, which in some cases vary greatly due to natural conditions such as topography or location along a stretch of water, the comparison of costs and benefits of such a measure, the relevant climate parameters and the remaining service life of assets.

The participants of the final workshop were asked about their assessment of the effort required for adaptation in their company respectively area of responsibility (Figure 8). The majority of the participants estimate the effort for adapting to the consequences of climate change as medium for the RCP2.6 scenario and as high for the RCP8.5 scenario. However, there are also estimates that the effort will be above or below this. Even for the RCP8.5 scenario, there are still estimates from participants that the effort will be low or very low. About one third of the respondents come from the port construction/infrastructure management sector and about half from the strategic sector.
How do you estimate the effort required to adapt your company/area of responsibility?

Figure 8: Result of the survey conducted during the final workshop regarding the effort required to adapt the company or area of responsibility to climate change.

The participants of the final workshop were also asked about their assessment of the greatest challenge in connection with adaptation to climate change. The greatest challenge is seen in dealing with uncertainties, followed by technical feasibility and financing (Figure 9).

Figure 9: Result of the survey conducted in the framework of the final workshop regarding the greatest challenges in relation to adaptation to climate change.

Uncertainties will not be eliminated due to the unknown future development of greenhouse gas emissions. Uncertainties can be addressed by keeping the timing of implementation flexible with the use of so-called adaptation pathways (step 4.5 of the PIANC guideline). In order to minimise existing uncertainties about
Do you think it is likely that you will deviate from the current recommendations in regulations in the future when implementing new construction projects in order to take a climate surcharge into account?

- Very likely
- Probably
- Rather likely
- Rather unlikely
- Unlikely
- Very unlikely
- Not specified

Figure 10: Result of the survey conducted during the final workshop regarding the consideration of climate surcharges, independent of current recommendations in rules and regulations.

Recommendations for adaptation can refer to take into account climate surcharges or at least to carry out sensitivity studies, to create hazard maps so that defence measures can be taken at vulnerable locations, or to adapt behaviour patterns. Table 7 shows an overview of significant climate parameters, their probability of change and recommendations for adaptation compiled on the basis of the results of the PortKLIMA project.
<table>
<thead>
<tr>
<th>Climate parameter</th>
<th>Probability of change</th>
<th>Recommendations for adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea level rise</td>
<td>Certain</td>
<td>+0.5 to +1.0 m of sea level rise until 2100 Consider implementation of a construction reserve Create flood hazard maps Identify influence on drainage capacity of receiving waters and groundwater levels</td>
</tr>
<tr>
<td>Temperature</td>
<td>Certain</td>
<td>Observe heat related operational restrictions especially in relation to steel components, e.g. bridges and switches, cool components if necessary Adaptation of work safety for employees, if necessary Consider increased cooling demand for buildings, machinery and electronics</td>
</tr>
<tr>
<td>Heavy precipitation</td>
<td>Probable</td>
<td>Sensitivity analysis: design value +10% Identify flow paths/create flood hazard maps Implementation of retention volumes, if possible Protection of assets from storm water run-off where required</td>
</tr>
<tr>
<td>Wind</td>
<td>Uncertain</td>
<td>No clear climate signal available. Therefore, currently no recommendation to increase design values. Review and practice safety measures against wind-induced projectiles</td>
</tr>
<tr>
<td>Air/ water chemistry</td>
<td>Uncertain</td>
<td>Observe and document affectedness</td>
</tr>
</tbody>
</table>

Table 7: Climate parameters, their probability of change and recommendations for adaptation

7 RESUME

As hubs in world trade, seaports are of central importance. At the interface between water and land, seaports will be particularly affected by sea level rise, but other extreme weather events such as high winds and heavy precipitation, as well as high and low water situations, and their impact on the entire logistics chain, will also become increasingly important. The adaptation of seaports to the consequences of climate change should be seen as a permanent task.

A potential approach to adapting seaports to consequences of climate change is outlined in the PIANC guideline. Despite the fact that climate changes are only gradually occurring and there are uncertainties regarding the consequences of climate change, the PIANC guideline provides a framework for action that can already be implemented today, which currently relates in particular to the assessment of risks, the adaptation strategies to be derived from this, and suitable monitoring systems for evaluating one’s own impact. Particularly when planning new assets with long service lives, appropriate climate surcharges may already be necessary today.

It is still possible to limit consequences of climate change to a tolerable level for seaports. Otherwise, seaports in Germany may be faced with considerable adaptation costs and operational downtime in the future. In this context, addressing the consequences of climate change highlights the importance of climate protection measures, the effect of which benefits significantly from immediate implementation.

In order to communicate current state of knowledge into practice, a continuous transfer of knowledge is of great importance. Information should be available as centrally as possible, but with a regional focus, and should be prepared for specific target groups. The involvement of professional associations and regulatory bodies supports professional planners, who have the technical know-how of possible adaptation measures, in taking adaptation to climate change into account appropriately. The forward-looking examination of climate change adaptation also has the potential to identify questions and thus initiate knowledge transfer between research and application at an early stage.

8 ACKNOWLEDGEMENTS

The work was carried out as part of the project PortKLIMA ‘Development and pilot implementation of educational modules for integrating climate change adaptation into the planning, construction and operation of seaports in Germany’ funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and financially supported by bremenports GmbH & Co. KG.
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Schwerpunkttes Schiffbarkeit und Wasserbeschaffenheit (SP-106) im Themenfeld 1 des BMVI-Expertenennetzwerks“, Bundesministerium für Verkehr und digitale Infrastruktur, Berlin.


SUMMARY

The resilience to climate change of seven German seaports was examined and both strategies and measures for their adaptation to the consequences of climate change are presented. The work was conducted as part of the project PortKLIMA – "Development and Pilot Implementation of Educational Modules for the Integration of Climate Change Adaptation in the Planning, Construction and Operation of Seaports in Germany". The basic framework for the study is the guideline of the PIANC Working Group 178 – "Climate Change Adaptation Planning for Ports and Inland Waterways", published in 2020.

The expected impact on the seaports involved in the project in the context of climate change, which can be observed in the ports themselves but also in hinterland logistics, is emerging. The future vulnerability of seaports depends to a large extent on the development of greenhouse gases and the associated consequences of climate change. Especially in a severe greenhouse gas mitigation scenario, the consequences for seaports in Germany can turn out to be manageable. However, if greenhouse gas emissions continue to rise uncontrolled, the consequences can be considerable, especially as a result of unabated sea-level rise.

From the current point of view, the most important adaptation measure is to implement an adaptation strategy in order to be able to objectively assess the impact on the port and to take future consequences into account in port management and development as early as possible. Seaports have always been subject to changing economic requirements, e.g. as a result of technical innovations or growth in ship size. From an economic point of view, it is therefore plausible to implement adaptation measures over time in the case of upcoming investment measures. Facilities with long service lives, such as flood protection facilities or locks, require early integration of possible climate impacts. From a planning perspective, recommendations for adaptation to climate change in regulations are urgently recommended in order to justify investments to be made using public funds.

RESUME


L’impact attendu sur les ports maritimes impliqués dans le projet dans le contexte du changement climatique, qui peut être observé dans les ports eux-mêmes mais aussi dans la logistique de l’arrière-pays, se dessine. La vulnérabilité future des ports maritimes dépend dans une large mesure de l'évolution des gaz à effet de serre et des conséquences associées du changement climatique. Dans un scénario d'atténuation des gaz à effet de serre, les conséquences pour les ports maritimes allemands peuvent s'avérer gérables. Toutefois, si les émissions de gaz à effet de serre continuent à augmenter de manière incontrôlée, les conséquences peuvent être considérables, notamment en raison de l'élévation continue du niveau de la mer.

Du point de vue actuel, la mesure d'adaptation la plus importante consiste à mettre en œuvre une stratégie d'adaptation afin de pouvoir évaluer objectivement l'impact sur le port et de prendre en compte le plus tôt possible les conséquences futures dans la gestion et le développement du port. Les ports maritimes ont toujours été soumis à des exigences économiques changeantes, par exemple à la suite d'innovations techniques ou de l'augmentation de la taille des navires. D'un point de vue économique, il est donc plausible de mettre en œuvre des mesures d'adaptation dans le temps lors des prochaines mesures d'investissement. Les installations ayant une longue durée de vie, comme les installations de
ZUSAMMENFASSUNG


Es zeichnen sich die zu erwartenden Auswirkungen auf die am Projekt beteiligten Seehäfen im Kontext des Klimawandels ab, die in den Häfen selbst, aber auch in der Hinterlandlogistik zu beobachten sind. Die künftige Verwandlungsfähigkeit der Seehäfen hängt in hohem Maße von der Entwicklung der Treibhausgase und den damit verbundenen Folgen des Klimawandels ab. Insbesondere in einem strengen Treibhausgasminderungsszenario können die Folgen für die Seehäfen in Deutschland überschaubar ausfallen. Steigen die Treibhausgasemissionen jedoch weiter unkontrolliert an, können die Folgen, insbesondere durch einen ungebremsten Meeresspiegelanstieg, erheblich sein.


RESUMEN

Se ha examinado la resistencia al cambio climático de siete puertos marítimos alemanes y se presentan tanto estrategias como medidas para su adaptación a las consecuencias del cambio climático. El trabajo se llevó a cabo en el marco del proyecto PortKLIMA – "Desarrollo e implementación piloto de módulos educativos para la integración de la adaptación al cambio climático en la planificación, construcción y operación de los puertos marítimos en Alemania". El marco básico para el estudio es la directriz del Grupo de Trabajo 178 de la PIANC – "Planificación de la adaptación al cambio climático para puertos y vías navegables", publicada en 2020.

El impacto previsto en los puertos marítimos que participan en el proyecto en el contexto del cambio climático, que puede observarse en los propios puertos pero también en la logística del interior, es emergente. La futura vulnerabilidad de los puertos marítimos depende en gran medida de la evolución de los gases de efecto invernadero y de las consecuencias asociadas al cambio climático. Especialmente en un escenario de mitigación severa de los gases de efecto invernadero, las consecuencias para los puertos marítimos en Alemania pueden resultar manejables. Sin embargo, si las emisiones de gases de efecto invernadero siguen aumentando de forma incontrolada, las consecuencias pueden ser considerables, sobre todo como resultado de la subida incesante del nivel del mar.
Desde el punto de vista actual, la medida de adaptación más importante es aplicar una estrategia de adaptación para poder evaluar objetivamente el impacto en el puerto y tener en cuenta las consecuencias futuras en la gestión y el desarrollo portuarios lo antes posible. Los puertos marítimos siempre han estado sujetos a los cambios en los requisitos económicos, por ejemplo, como resultado de las innovaciones técnicas o del crecimiento del tamaño de los buques. Desde el punto de vista económico, es por tanto plausible aplicar medidas de adaptación en el tiempo en el caso de las próximas medidas de inversión. Las instalaciones con una larga vida útil, como las instalaciones de protección contra inundaciones o las esclusas, requieren una integración temprana de los posibles impactos climáticos. Desde el punto de vista de la planificación, es urgente recomendar la adaptación al cambio climático en la normativa para justificar las inversiones que se realicen con fondos públicos.