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The Relationship between the Local Distance/Length Ratio of a Coastal Structure and the Corresponding Impact on the Littoral Drift

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Abstract: Within the surf zone, a coastal structure is very likely to have an impact on the littoral drift (e.g. Fredsoe et al., 1992). Proximity to the coastline (x) and width of the structure (L_B) have been combined (L_B/x) to provide guidelines on avoiding salient development (Mangor et al., 2017). To assess the functional design of a planned insular harbour and potential shoreline impacts, various stakeholders worked with DHI to complement such guidelines by applying numerical modelling tailored to site specific processes. Therefore, a modelling exercise including all relevant coastal processes was performed using MIKE21 FM by DHI (DHI, 2016). Baseline and design scenarios were examined including different port geometries up to 130m wide with a maximum distance of 760m (6m depth contour) from the coastline. Critical L_B/x values typically range between 0.17 (Dally and Pope, 1986) and 0.50 (Nir, 1982). The analysis by DHI WASY (2018) shows the development of a salient for $L_B/x > 0.17$ - 0.20 and identifies a larger impact for higher L_B/x ratios. However, the model goes beyond a simple threshold value recommendation by helping to predict the location and geometry of the salient for various scenarios and by including the temporal scale of those impacts.

Keywords: Numerical shoreline modelling, LB/x ratio, morphologic changes Introduction

1 Introduction

The current study was undertaken as a consultancy project co-funded by the European Union to help the federal state of Mecklenburg-Western Pomerania represented by the Agency of Agriculture and Environment (StALU MM) in shortlisting preferred options for the necessary construction of an emergency harbour with additional functionalities. The chosen coastal stretch is a sensitive bay due to environmental (location within a nature reserve) and economic (tourist region) reasons. The purpose of the study was to use advanced techniques to complement empirically derived expert knowledge (e.g. Mangor, 2017) and find out to what degree computational process-based methods provide added informative value in the decision making to optimize proposed harbour layouts in terms of shape, size and distance to the coast.

2 Methods

2.1 Study area

The preferred location currently considered for the planned harbour lies exactly North of Prerow (German Baltic Sea) and acts as an extension to the existing sea bridge. To cover all the relevant coastal processes, the study area comprises the entire beach between a location west the peninsula Darßer Ort called Teerbrennersee and a forest area near Zingst at the eastern boundary of the study area. This coastal reach stretches across 23 km and the model extents about 2km offshore (near the peninsula) and 6 km offshore in the eastern end of the study area. The peninsula Darßer Ort is effectively a large sandspit and is morphologically very active. The beach along Prerow, which lies within a natural reserve, is relatively stable but is subject to wave-induced sedimentation and erosion, partly affected by nourishment programs and groynes near Zingst. The peninsula in the west shields a large proportion of western waves and therefore wave activity at the proposed harbour location is predominantly dominated by waves from the North East.

Fig. 1. Extract of the study area (DHI WASY, 2018).

2.2 *Coastal processes within the surf zone*

The processes relevant to erosion and sedimentation at the Prerow coastline are predominantly wave-induced. Tidal activity is very low. Cross-shore sediment movement at dune and beach type coastal reaches is mainly affected by storm surges and therefore – for this investigation - neglectable compared to the littoral drift component of the surf zone. The magnitude and the characteristics of the littoral drift are strongly dependent on the angle of incidence, significant wave height, directional spreading of the waves and in the case of obstacles within the surf zone diffraction processes. These parameters describe the level of energy dissipation relating to breaking waves. The breaking waves induce wave-period averaged currents and generate turbulent eddies which penetrate to the sea-bed. The latter increases sediment suspension into the water column. The combination of the suspended sediment and the wave induced currents leads to transport of sediment along the coastline – this is also known as littoral drift. The littoral drift depends primarily on the wave breaking process and on secondary parameters such as grain size (fall velocity) and the coastal morphology (flow resistance, slope of the profile).

This equilibrium state is disrupted when an obstacle is placed within the surf zone, by blocking both the sediment transport and diffracting the waves, thereby creating a zone of reduced sediment transport on the lee side of the structure that typically leads to sand accumulation (salient or tombolo development, e.g. Mangor et al., 2017).

2.3 *Numerical methods and software used*

Whereas the physical concepts of the littoral drift appear relatively simple, a mathematical description that accurately describes these processes is far from straightforward. A bulk empirical method to estimate the accumulated annual transport is provided by the CERC formula (e.g. CERC, 1984, 1993):

$$Q = \frac{K}{16\sqrt{\gamma_b}} \rho g^{3/2} H_b^{5/2} \sin(2\theta_b)$$

Where Q = littoral drift (m^3a^{-1}), K is an empirically derived coefficient (around 0.32 for sandy beaches), γ_b is the relative density of the sand (1.65 gcm^{-3}), H_b is the wave height at the breaking point, θ_b is the angle of incidence of the waves at the time of breaking and g is the acceleration constant of 9.81 ms^{-2}.

The formula includes the most important input parameters and describes the exponential increase of sediment transport with wave height. However, a major deficit of such an approach is the fact that the spatial variability of the wave field, currents and grain size distribution is neglected. In addition, the CERC formula is only able to calculate bulk transport rates. To effectively assess transport rates along the shore and identify areas with sand excess and deficits, a robust numerical approach should be able to provide calculations of the net littoral drift for a given time frame.

In this project, a fully integrated model to simulate waves, currents, sand transport and morphologic changes was applied. The model consists of the modules MIKE21 Spectral Wave (SW) FM, MIKE21 Hydrodynamic (HD) FM, MIKE21 Sand Transport (ST) and MIKE Shoreline model (SM) (Fig. 2).

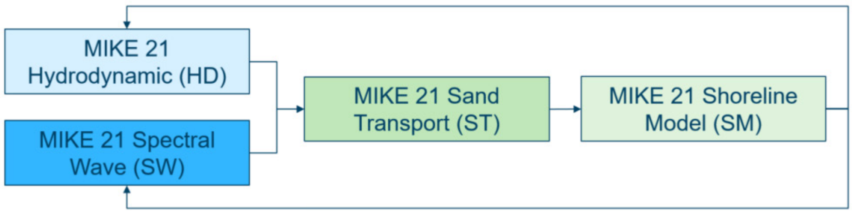

Fig. 2. Fully coupled coastal sediment transport model.

A full description of the numerical methods behind the spectral wave model is beyond the scope of this paper. It is, however, important to realize that the SW component of the model describes all relevant wave processes, including wind-induced wave generation, non-linear wind-wave interactions and energy dissipation due to white capping, bottom friction, depth-induced wave breaking (DHI WASY, 2018). The model also has robust numerical schemes to describe refraction, shoaling, diffraction and reflection processes. Finally, the SW model is capable of modelling the interaction between currents and waves, thereby providing important boundary conditions for the hydrodynamic component of the calculations (DHI, 2016). The depth averaged HD model uses a finite volume approach to iterate the depth-averaged shallow water equations, including momentum and convective acceleration terms. Both effects important to include spatial lag effects at obstacles, such as wave breakers and insular harbours. The dynamically coupled ST model then uses the conditions calculated by both the SW and HD model to calculate sediment transport rates within the surf zone and beyond. This model uses a range of lookup tables that pre-defines parameter ranges for grain size and wave breaking parameters (DHI, 2016). Finally, the SM model is used to calculate morphological changes within the surf zone by respecting the equilibrium profile assumption (Kristensen et al., 2013). The morphological changes are reflected within the next time step of the HD, SW and ST calculations.

2.4 Baseline and scenario modelling

Baseline model setup and boundary conditions

To assess the effect on the coastline of various harbour layout designs, the current situation needed to be adequately represented by a model. The modelling concept has been described in the above paragraph. An essential component of the model is the finite element mesh, which consists of triangular elements with a fine resolution (12 m) within the surf zone and progressively larger elements further offshore. The elevation of the mesh nodes is derived from a previously prepared terrain model. The bathymetry was derived by interpolation of coastal profiles and wave conditions for the model boundary were extracted using an existing hindcast model and validated with measurements. The hydrodynamic conditions to be simulated included wind, waves, water level, currents and salinity. The results from this large-scale model were extracted at the boundaries of the nested coupled model (see Study Area 2.1) and applied as input conditions. Other relevant parameters for the MIKE21 model are summarized in Tab. 1. The simulation period was chosen for appr. 12 years, using hindcast wave condition inputs between 01/2003 and 12/2014 to predict the long-term changes to the coastline related to the planned harbour, assuming the chosen period to be representative also for the expected future wave climate in the region (DHI WASY, 2018).

Tab. 1. Parameters used in the shoreline model setup

Parameter	Value or description
Eddy viscosity	0.28 m^2s^{-1}
Bed friction (HD)	15 – 50 $m^{1/3}s^{-1}$
Critical Shields parameter	0.05
Sand density	2.65 kgm^3
Grain size d_{50}	0.17 mm
Grain distribution parameter	1.5
Wave formula	Quasi stationary directionally decoupled formulation
Spectral discretization	360° in 25 direction, 15° per bin
Feedback on water levels	Included
Diffraction	Included
Wave breaking	α = 1, γ_1 = 0.8 (depth), γ_2 = 2 (steepness)
Nikuradse roughness (bed friction SW)	0.01 m

Baseline model validation

In coastal morphological situations, model calibration or validation is typically a difficult exercise. Direct measurements of the littoral drift and changes in the coastal profile are rare and were not available in the case of the Prerow coastline. However, proxy data can be used for validation. In most cases, they need to be considered with care.

Tab. 2 summarizes the proxy data used for model validation and comments on the suitability for the model calibration. The model predicts the coastal movements between the bounds indicated by the aerial photographs and digitized coastlines and adequately represents the stretches of areas prone to either erosion and sedimentation including the location of the observed transition zones (DHI WASY, 2018).

Tab. 2. Data used for model validation

Parameter	Value or description
Aerial photographs (2002,2005, 2007, 2010, 2013 and 2015)	Snapshot of the coastline without knowledge of the exact date and water level
Digitized coastlines (1998,2009, 2012 and 2014)	Terrestrial survey on a beach can be subjective, flat topography leads to the identification of different lines with elevation at sea level
Expert discussions	Provide knowledge for areas with tendencies for either erosion or sedimentation, but do not give reliable quantifications of the shoreline movement
Nourishment quantities	Relatively accurate indications of sand volumes (m^3) for different times, but difficult to link to the net shoreline movement
Dredging quantities at the existing harbour near the peninsula	Indication of local quantities, not applicable for coastal reach calibration
Previous studies	Calibration in previous studies also faced the issues described above

Modelled scenarios
Conceptual and economic considerations have led to a pre-selection of seven harbour layouts that vary in size, shape and distance from the coastline (Tab. 3). The structures were georeferenced and included as polyline features in the model setup. The HD model applies a weir formula (in the case of overtopping), whereas the SW model calculates energy dissipation and wave transformation. The simulations were performed to better understand the impact of the three parameters above on the temporal and spatial scales of salient development.

Tab. 3. Modelled scenarios (layouts)

Scenario	Shape	Max. width (m)	Distance of widest section from the coastline (m)	Depth contour at port entrance (m)	L_B/x
D1	Droplet	105	612	4.5	0.17
D2	Droplet	105	698	5.0	0.15
D3	Droplet	130	578	4.0	0.22
D4	Droplet	130	724	5.0	0.18
D5	Droplet	130	908	6.0	0.14
C1	Circle	120	507	4.0	0.24
C5	Circle	155	841	5.0	0.24

3 Results and discussion

3.1 Baseline situation

A statistical analysis of the wave rose at the planned harbour location (DHI WASY, 2018) shows that larger waves predominantly hit the coast from a north easterly direction. In combination with the current coastal shape this situation creates a tilting point near the location of the current sea bridge: the net littoral drift is towards the west and its magnitude decreases in both directions away from the harbour location (Fig. 7). This generates a zone more prone to erosion in the eastern section next to the port location and a tendency for sand accumulation for a 2.5 km stretch west of the port location. Any disruption to the wave condition in this section is therefore likely to have an impact on the coastline.

3.2 Scenario results

The model results were used to derive a better understanding on the impact of the planned structure on the coastline and compare the results to literature findings.

Effect on wave climate
The patterns of wave deflection for the modelled scenarios were visualized by plotting the 1-year storm event (return period of one year) with a predominant north-easterly direction. The structure is responsible for a reduction in wave height between the structure and the coastline with the lee zone distorted along a northeast-southwest axis as opposed to perpendicularly to the coastline.

A comparison between Fig. 3 and Fig. 4 shows the effect of structure size on the lee zone extent. The harbour entrance of both structures are located at the same distance from the coastline (near the 5m depth line), but the larger structure (D4 in Tab. 3) has a more pronounced effect on significant wave height reduction than D2.

A closer distance to the coast further enhances the leeside effect, creating a zone of smaller waves between the structure and the coastline (Fig. 4 and Fig. 5). Finally, a circular harbour blocks a lower proportion of larger waves that are responsible for sediment motion initiation. For example, Fig. 6 exemplifies the case of a 1-year storm event (return period of one year), where fewer waves between 0.6 and 0.7 reach the shallow area of the coastline than in the case of a droplet shape with a similar effective breakwater length and located at the same distance from the coast (Fig. 5).

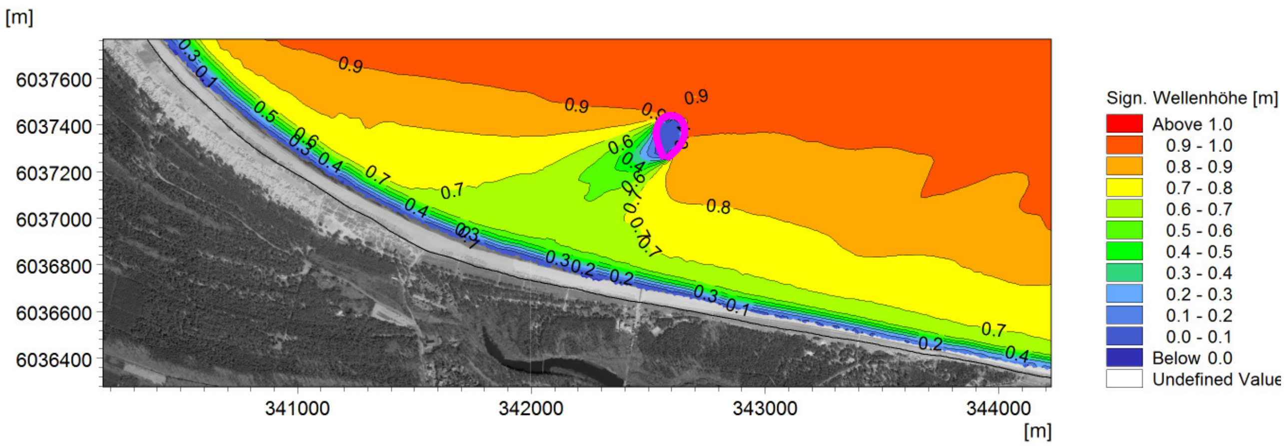

Fig. 3. Wave field for a representative 1-year storm event (return period of one year) for the scenario D2

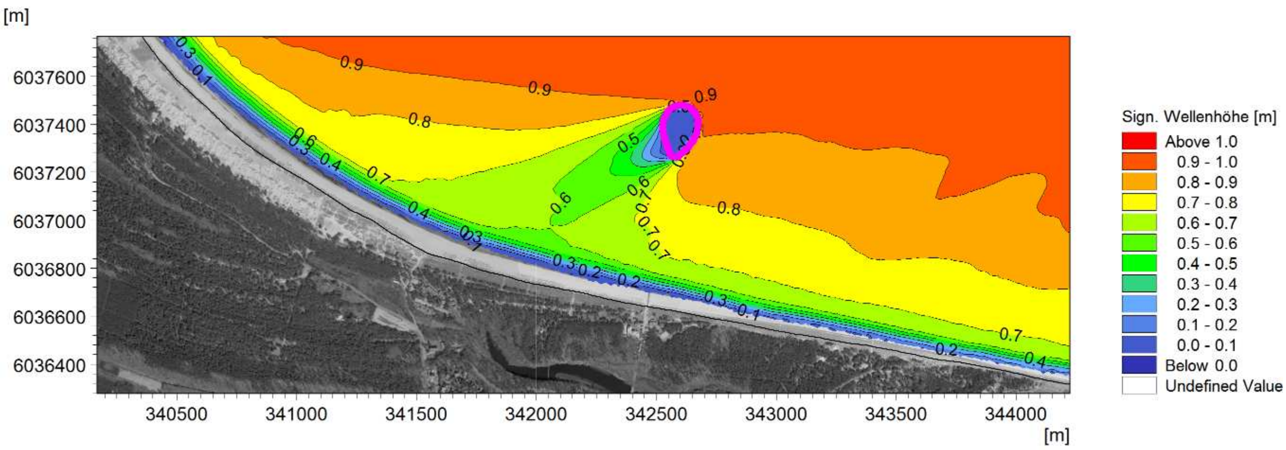

Fig. 4. Wave field for a representative 1-year storm event (return period of one year) for the scenario D4

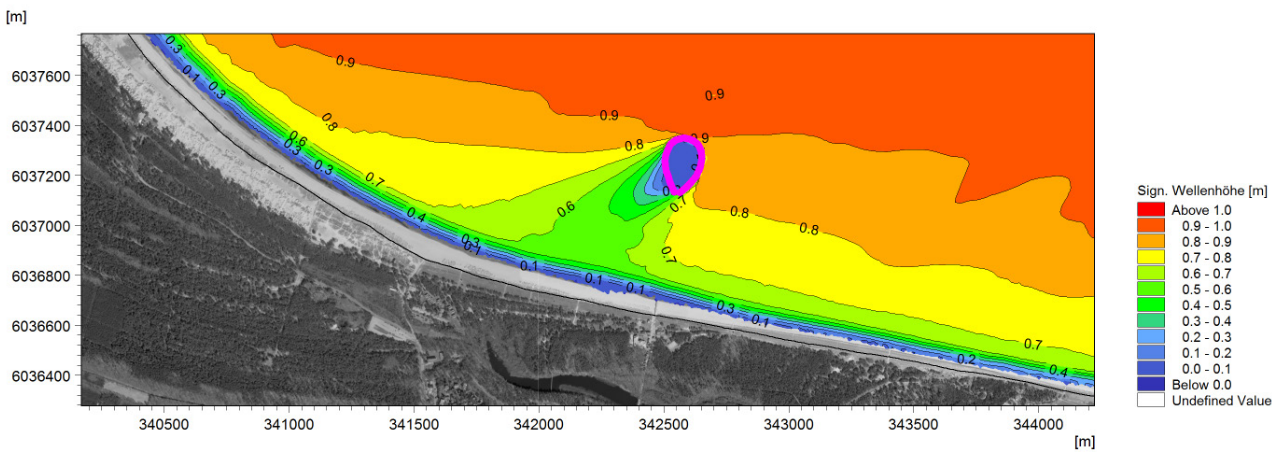

Fig. 5. Wave field for a representative 1-year storm event (return period of one year) for the scenario D3

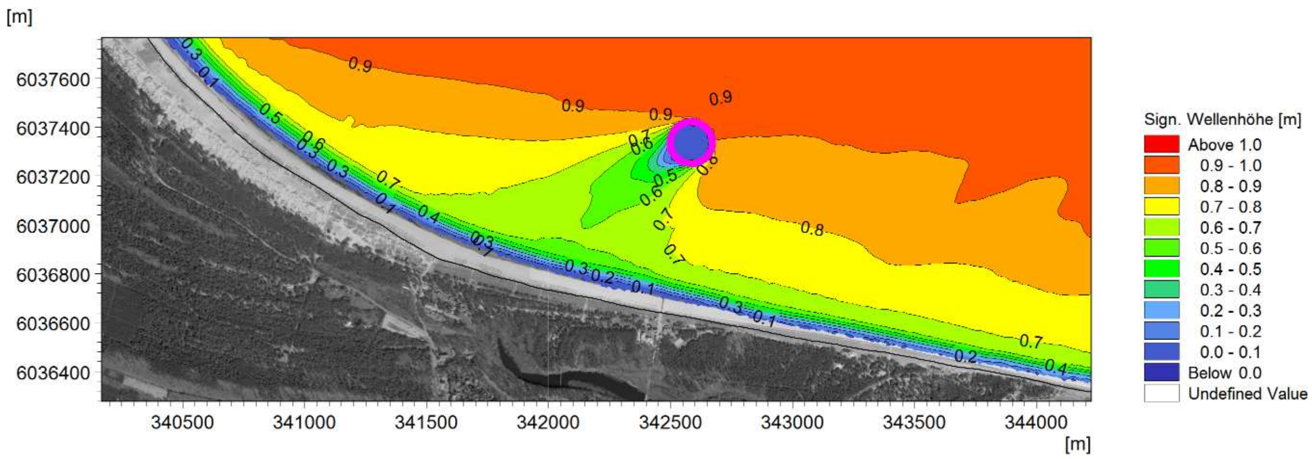

Fig. 6. Wave field for a representative 1-year storm event (return period of one year) for the scenario C5

Effect on coastal transport rates and coastal morphology

The change in nearshore wave state described above is directly responsible for the development of a salient in the lee zone of the structure. As shown in Fig. 7., the gradient in the accumulated littoral drift over 12 years is particularly steep in the section directly west of the planned harbour structure (divergence between the solid and dotted grey lines). This reduction in sediment transport is an indication of sand accumulation in this coastal reach, leading to salient development. Eastward of the structure, the magnitude of the littoral drift increases compared to the baseline situation, leading to a slight erosion in this zone.

To visualize the development of a salient compared to both the As Now Situation (yellow line) and the predicted baseline situation (blue line) in 12 years, the modelled coastline changes for the calculated scenarios (pink line) were plotted (Fig. 8).

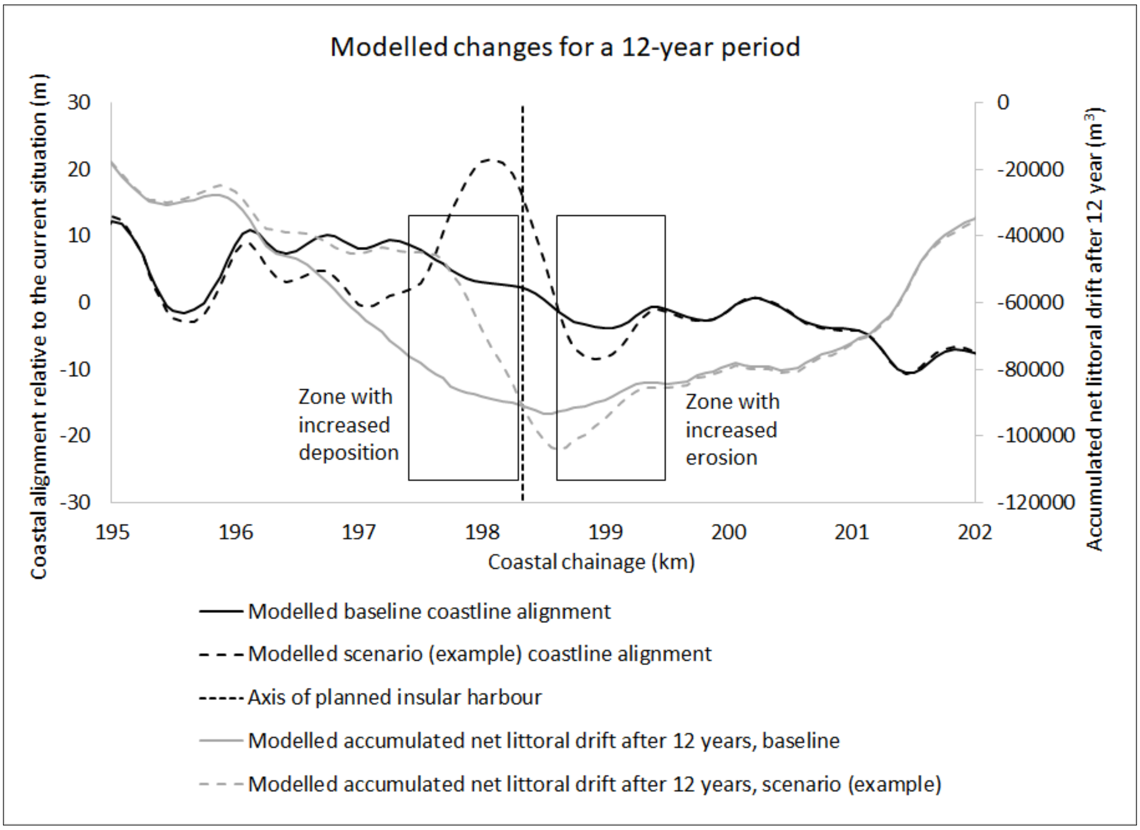

Fig. 7. Effect of the coastal structure on sediment transport rates and coastal alignment.

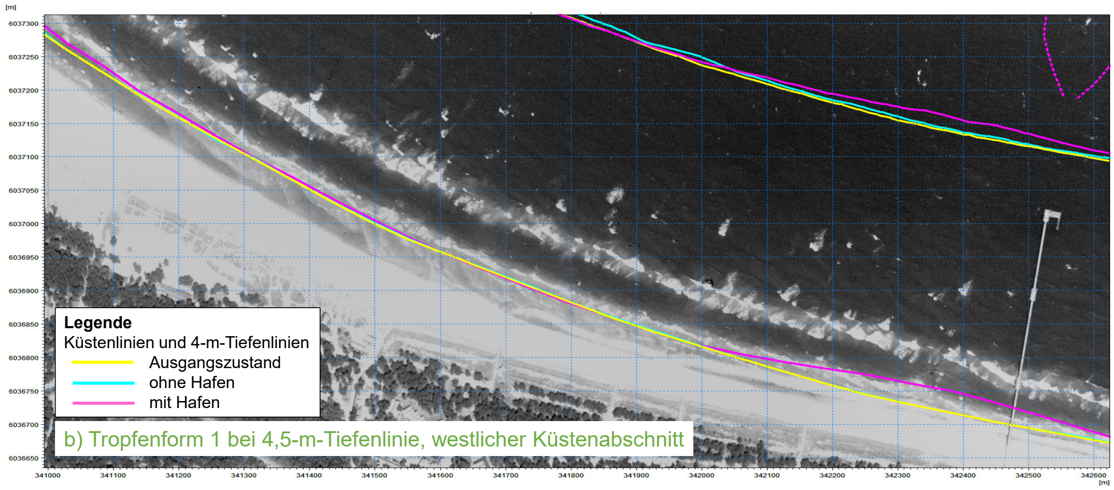

Fig. 8. Example of the change in coastline alignment compared to the baseline situation.

3.3 *Relationship between L_B/x and salient development*

The scenario modelling confirmed the relationship between distance (x) and size (effective breakwater width L_B) of an obstacle in the surf zone and the resulting impact on the coastline. The effect is described among others by Mangor et al. (2017) (Fig. 9) and Kristensen et al. (2013), who looked at those mechanisms using a very similar modelling approach. According to Mangor et al. (2017), a visible salient development is expected when $L_B/x > 0.2$, with tombolo development likely at $L_B/x > 0.9$. For this relationship to be valid the structure must lie within X_{80}, i.e. within a distance to the coastline where at least 80% of the littoral drift takes place. Other coastal experts suggest L_B/x values as low as 0.125 (e.g. Dally and Pope, 1986) and as high as 0.5 for salient development (e.g. Nir, 1982).

In the current study, all the scenarios except those near the 6m depth contour line ($L_B/x = 0.15$) and the large droplet shape further out (6 m contour) with a L_B/x ratio of 0.14 show a visible impact on the coastline. The study also shows that larger values of the size/distance ratio typically leads to a more pronounced salient, both in terms of width and accumulated sand volume. For example, the largest droplet shape structure, when located at the 4 m depth contour (around 437 m from the coastline) leads to the development of a 30 m wide salient compared to the baseline situation, whereas the modelled width of the salient for the same structure at the 6m depth contour line (around 755 m from the current beach location) is below 15 m and therefore neglectable with the tolerance considerations of the natural coastline development (DHI WASY, 2018).

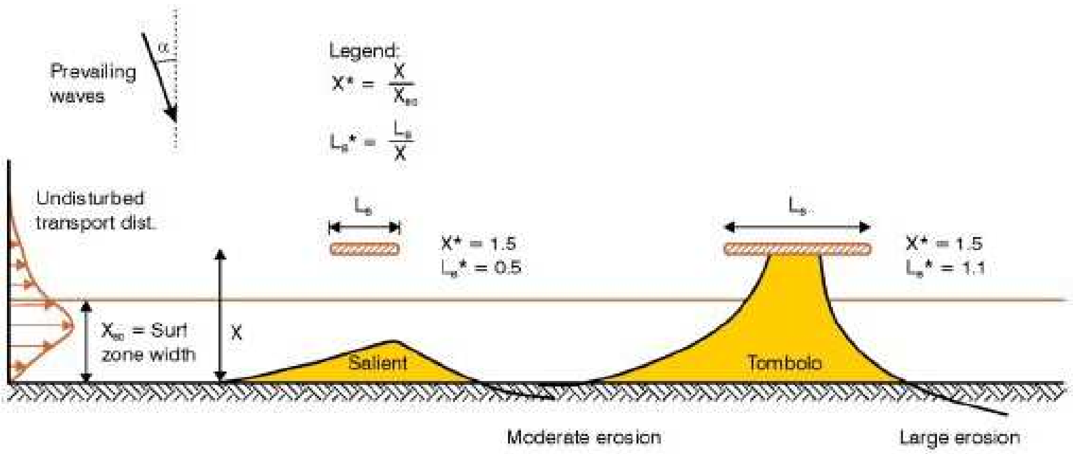

Fig. 9. Relationship between the L_B/x and the salient development, in Mangor et al. (2017).

Therefore, the modelling results for this specific area lead to recommending a more conservative L_B/x threshold value to help deciding on potential insular harbour layouts compared to the recommendations by coastal experts like Nir (1982). However, the modelling exercise also confirms that the empirical relationship is not universally valid and any significant coastal development in sensitive areas should be subject to side specific testing using more advanced techniques such as the modelling approach used in this study.

The differences in the interpretation of L_B/x are not only related to the techniques applied in the quantification, but also to the particularities of the site that was examined. Salient development in this study is primarily the result of the harbour location at the inflection point of the curved coastline and the predominant direction of the waves sufficiently strong and frequent to cause most of the sediment transport in this specific coastal reach. In many coastal areas across the world, wave conditions are much less uniform (e.g. Holthuijsen, 2010). Finally, the model looks at relatively complex structure geometries as opposed to straight line breakwater features, which have a more predictable impact on the coastline.

4 Conclusions

Numerical coastal models (Kristensen et al., 2013; DHI WASY, 2018) provide detailed insight into coastal processes and allow further refinement of estimates done by empirical formulae and observations (e.g. Mangor et al., 2017; CERC, 1993). This is achieved by using spatial and temporal boundary conditions such as bathymetry, sediment properties and grain size and by applying advanced numerical algorithms. A major drawback of applying modelling to quantifying coastal changes is that the relatively high effort of preparing and running such models is accompanied by a high degree of freedom in the parameter definition used in these models (e.g. Kristensen et al., 2013). These uncertainties can typically be reduced using expert evaluations but are rarely backed by robust calibration and validation data.

The model was able to represent the observed coastal process for the baseline situation and to confirm the effect of the L_B/x parameter on the extent of salient development. The model identified a sensitive reaction of the coastline alignment even for structures relatively small and far off the coast, hereby backing the more conservative estimates of critical L_B/x values (e.g. Dally and Pope, 1986) as opposed to the higher values proposed by Nir (1982). Furthermore, the model was able to provide further information on the exact location of the salient structure (which is shifted slightly westward to the normal axis) and temporal scales for the sand accumulation. The study finally concludes that the modelling-based approach complements valuable expert knowledge and globally accepted guidance notes (e.g. CERC, 1984) by considering site specific issues such as the predominant wave conditions, the alignment of the coast in relation to the wave field and the local bathymetry and sediment properties.

After weighting of advantages, disadvantages and uncertainties of the model in practice DHI recommend an LB/x threshold value of roughly 0,2 for the functional planning of the island harbour. This recommendation accepts the development of a relatively small, wide salient with only small erosion tendency east and west from the existing seabridge. Furthermore, DHI recommend monitoring of shoreline development and potential use of accumulated sand for compensation of sediment deficits and for coastal protection.

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