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Development of an Outdoor Wave Basin to Conduct Long-Term Model Tests with Real Vegetation for Green Coastal Infrastructures

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Abstract: The demand for physical model tests with real vegetation is increasing due to the current trend to elucidate the performance and durability of green coastal infrastructures to ensure and promote ecosystem services. To address this demand, a new outdoor wave basin (OWB) was built in August 2017 at the Ludwig-Franzius-Institute in Hannover, Germany. This paper reviews the general characteristics and the ongoing development of the new OWB. First insights into the long-term development of the ecosystem services of different grass revetments are discussed in terms of their ecological value and safety standards of sea dikes. Focus is placed on the resistance and ecological value of different grass mixtures that are typically applied on sea dikes situated along the North Sea. Further research concepts are briefly described to highlight how experiments in the new OWB may contribute to the current understanding and design recommendations of green coastal infrastructures. The operation of the OWB enables the performance of long-term experiments over seasonal growth stages of coastal vegetation using either fresh or seawater with wave load stresses and varying sea water levels. The first conducted experiments with different grass revetment combinations mimic typical storm surge conditions with a constant wave load (with a duration of up to 10 hours every second week) on a natural dike.

Keywords: outdoor wave basin; long-term development; vegetation development; ecosystem services; nature-based

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1. Introduction

Traditionally coastal protection measures have been designed and optimised in terms of safety levels and costs, with minor consideration for the environment. Practical guidelines for coastal structures (e.g., the Shore Protection Manual [1], the Coastal Engineering Manual [2] and the Overtopping Manual [3]) are widely applied and conventionally rely on so-called hard solutions (e.g., dikes, seawalls or breakwaters). As the importance of sustainable development is increasingly recognised, greater emphasis is placed on designing environmentally friendly coastal structures. As such, soft solutions (e.g., dunes, seagrass meadows, saltmarshes and mangrove forests) are increasingly considered. The combination of coastal habitat (e.g., salt marshes) with hard solutions—known as hybrid infrastructure—is another way to implement soft solutions [4–7]. The potentials and performances of soft solutions are strikingly outlined [8] but still ineffectively addressed in terms of reliable and practical design guidelines [4,9] that consider ecological and engineering aspects in a mutual approach.

To incorporate coastal safety and other ecosystem services of green infrastructure in practical design guidelines, a deeper understanding of the interaction between soft solutions and hydraulic boundary conditions is essential.

In the past, investigations were conducted to estimate the dissipation of hydrodynamic energy by vegetation for various conditions and functions [10]. For example, the investigation of the failure of grass cover layers at seaward and shoreward dike slopes by Piontkowitz [11] or through the Sheldebak test in 1994 [12]. However, most of the studies used either artificial vegetation or focused on certain life stages of the particular vegetation by conducting only short-term physical model tests [13–16]. As pointed out by the ecosystem engineering approach to the management (EAM) of infrastructure by Hastings et al. [17] and the Building with Nature (BwN) approach by De Vriend [18] and proven from field and laboratory studies by Narayan et al. [8], one of the major knowledge gaps is the long-term development of nature-based sustainable solutions addressing performance and design of green coastal infrastructures. Physical model tests under controlled boundary conditions are required to study the ability of vegetation to adapt when exposed to hydraulic stresses. Recently, Silinski et al. [19] showed that the wave dissipation due to specific vegetation properties is affected by wave exposure. In this case, the ecosystem services of tidal marsh vegetation vary significantly between locations with different hydraulic boundary conditions. These findings should be considered in the design of ecosystem-based coastal protection measures with real vegetation. Thus, increasing demand for the highly interdisciplinary physical model tests with real vegetation and guidelines for the conduction of these experiments arises. Lara et al. [20] reviewed these issues and pointed out the complexity by defining a guideline for experiments with real vegetation in laboratories. Concerning the performance of long-term physical model tests, it is of utmost importance to mimic the natural conditions over seasonal cycles and vegetation growth phases. As such field studies are considered the most suitable option to deliver the most reliable results. However, results of field studies are also subjected to uncertainties due to transient boundary conditions, lack of control and limitations of monitoring techniques [21–23]. Controlled boundary conditions are essential to develop profound knowledge with a detailed understanding of the interactions between vegetation and biotic and abiotic factors. Thus, an outdoor wave basin is the most consistent and cost effective method for the development of green coastal infrastructures with ecosystem services of regional vegetation [20].

1.1. Impact of Waves on Coastal Ecosystems

Numerous field studies show that the development of coastal ecosystem and its services are affected by wave load [24–29]. Firstly, the rough environmental conditions in the wave impact zone result in a decreasing ecological niche leading to a limitation of the species richness in the coastal ecosystems [24]. Secondly, wave loads influence the coastal ecosystem characteristics like shoot density, expansion and survival rates of the shoots [27]. Bos et al. [27] showed a decrease in the survival rate of eelgrass as exerted stresses, due to wave loading, increased. Additionally, the wave loads change the zonation of vegetation within the coastal ecosystem [28,30]. The vertical zonation can occur during different life stages of the vegetation and result in a species-specific occupation of different water-depth zones inside the coastal ecosystem. Finally, the direct and indirect effects of wave load influence the individual mechanical characteristics of the vegetation [26]. Coops and Van der Velde [22] investigated the effect of wave load on the stem height of two seagrass species. Investigating four different helophytes, the direct and indirect effects of wave load were identified by Coops et al. [31]. The study provided evidence for the relation between increased biomass productions as wave exposure decreases. The findings of Blanchette [32] are in agreement with the findings of Coops et al. [31] showing the same relation for intertidal plants and their adaption to wave load. A decrease in stem height of a salt marsh leads to reduced wave attenuation [16] and a decrease of the effective ecosystem services of the coastal ecosystem [19,32]. Taking into account that wave loads exceed the boundaries of the coastal ecosystem during storm surges the review of the aquatic and littoral vegetation has to be extended for terrestrial vegetation. Therefore, the direct effects of wave loads are interpreted as mainly mechanical induced stress due to the frequent drag forces in combination with the excessive bending of the stems during wave run-up. The indirect effects of wave loads are interpreted as a loss of available plant nutrients in the topsoil. The findings of 80 studies are reviewed by Biddington [33], confirming the expected analogies between aquatic, littoral and terrestrial vegetation in their capability for adapting to mechanical stress. The review by Biddington [33] also highlighted various adaptations of plant growth, development and physiology by showing a wide range of mechanical induced stress with numerous adaptation strategies of the vegetation. Thus, the impact of wave loads on the coastal ecosystem can be characterized as dynamic and complex interactions affecting the ecosystem services of the environment.

1.2. Methodological Approach

Construction and design processes of coastal infrastructure along the European coastlines adhere reliably protect and safeguard the coastal hinterland from wave attack and storm surges. As highlighted by Schoonees et al. [4], traditional coastal structure provide limited ecosystem services in any proper design or maintenance approach. According to the ecosystem engineering approach, a high potential for increasing the ecosystem services of coastal infrastructures while preserving or possibly even enhancing the existing safety standards can be found in coastal infrastructure with vegetation [17]. To improve the design and maintenance of those compound coastal infrastructures, a profound understanding of the complex long-term performance and durability of vegetation development under altered metocean and hydrodynamic stresses, for example, waves, storm surges or sea level changes, are inevitable [34,35]. Thus, a new outdoor wave basin (OWB) has been developed and installed in the Ludwig-Franzius-Institute, Leibniz University Hannover, Germany in order to formulate practical design guidelines, considering ecological and engineering aspects in a mutual approach. As a pilot research study in the new OWB a typical sea dike in prototype scale has been erected and tested under realistic, long-term wave loading for innovative monitoring approaches within the Ecodike project (see Section 3).

The aim of the pilot project is to enhance the ecosystem services of dikes and revetments while preserving or possibly enhancing the existing safety standards. A controlled investigation of the effect of wave load on the vegetation development and resistance for sea dikes is required in order to reliably determine wave run-up reduction and mitigation of overtopping as grass revetment. Consequently, a concrete basin was built in August 2017 enabling multiple and faster model constructions due to the use of heavy machines inside the basin.

2. Outdoor Wave Basin

2.1. Dimensions and Construction

The OWB has been constructed adjacent to the large wave flume (GWK) of the Coastal Research Centre (Forschungszentrum Küste, FZK) and the 3D-wave-current-basin (WSBM) in the Northern city limit of Hannover, Germany. Due to a direct connection to the neighboured shipping channel an additional natural water reservoir is available besides the groundwater connection via a drain sump. The entrance of the OWB is designed for easy access by large trucks and to enable direct unloading of bulk material inside the basin. Furthermore, it is possible to use wheel loaders inside the OWB with up to 40 t for a fast model construction. The OWB is 24.10 m long and 14.2 m wide, containing a 12.55 m long and 14.2 wide deep section (see blue rectangle in Figure 1B). The maximum water levels are 0.8 m at the wave maker and 1 m in the deep section. The surrounding walls have a height of 1 m at the wave maker position and 2 m at the deep section which enables water levels up to 2 m for certain model setups. The OWB is also designed for tests with seawater. Those experiments would be conducted using a flexible PVC water tank as a closed system with water treatment next to the OWB (see Section 2.4). For test campaigns which require remote sensing, a 10 m high observation tower is available next to the OWB (see Figure 1A). The empty basin is shown together with the general wave maker position marked with a green rectangle in Figure 1B.

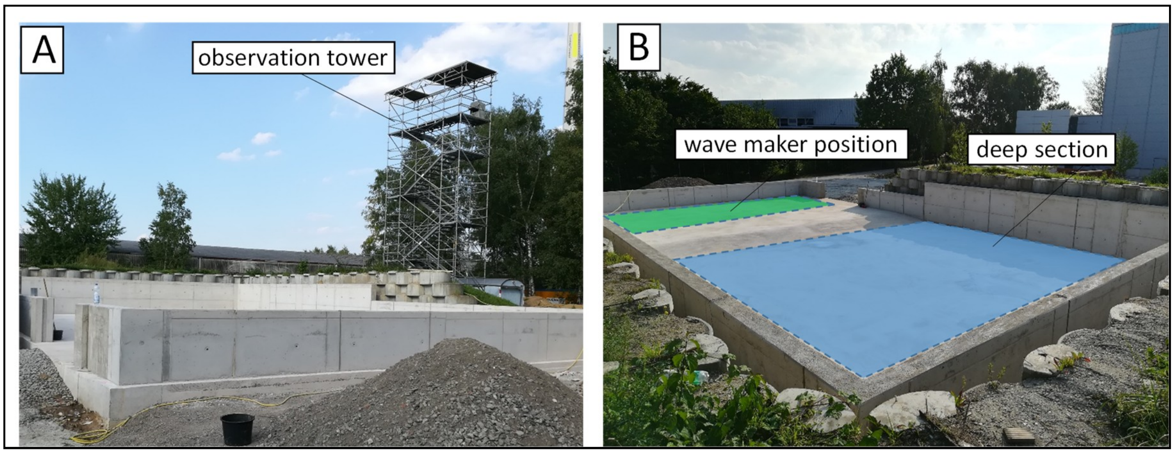

Figure 1. New outdoor wave basin during construction with observation tower (**A**) and empty basin after finishing the concrete works (**B**) in August 2017.

The deep section on the right-hand side in Figure 2 is 0.2 m lower than the marked wave maker position. This allows space for toe protection for model dikes (see Section 3) or the root development for model setups with imbedded vegetation.

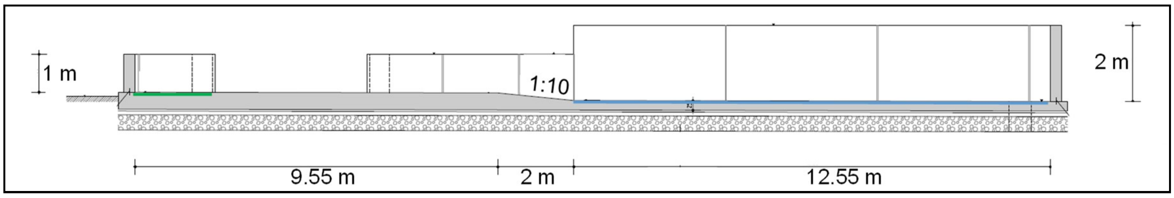

Figure 2. Profile of the outdoor wave basin with wave maker position (green) and deep section (blue).

2.2. Wave Maker

The DHI piston type wave maker system consists of three independent wave maker elements with an adjustable wave paddle width of 3 to 5 m. Thus, waves can either be generated over the total width or if necessary only in a selected section of the basin. The piston type wave maker elements are each driven by a hydraulic cylinder and are capable to generate a maximum stroke of 0.60 m. The wave maker motion and acceleration are controlled with a PC with Ethernet connection to the wave maker. The signals for the generation of irregular waves are computed from empirical energy density spectra (e.g., JONSWAP). The maximum water level at the wave maker (0.6 m) allows the generation of wave heights up to H_s = 0.25 m with periods of up to T_p = 3 s (see Figure 3A). An active wave absorption technique up to second order is about to be integrated in order to enable enduring modelling environments, thereby avoiding abnormal sea state conditions in the basin. Figure 3B shows the wave maker elements with a width of 7 m, which are fixed by their own weight and additional concrete blocks.

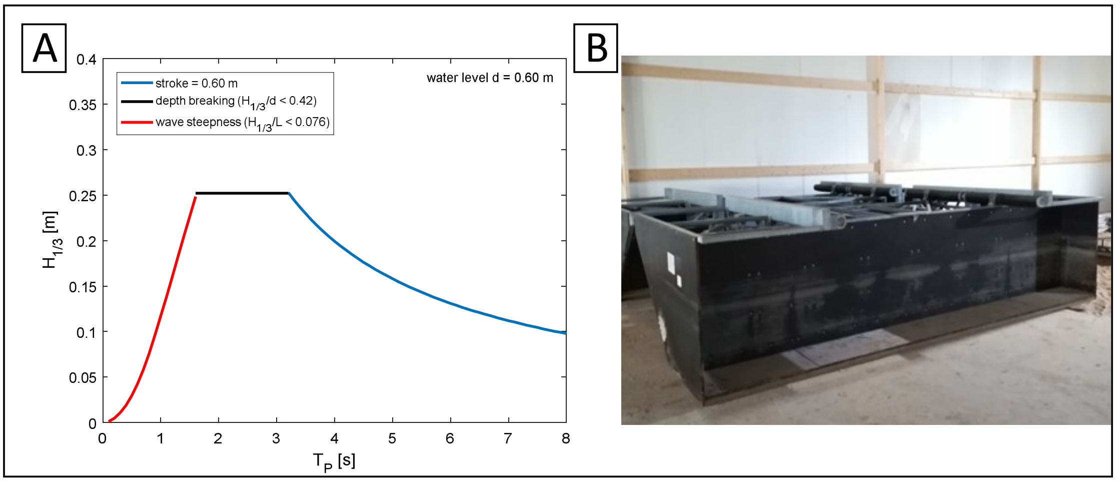

Figure 3. (**A**) Wave parameters for OWB (theoretical values, 90% practical reachable) and (**B**) Two DHI piston type wave paddle elements with a maximum width of 7 m and height of 1 m.

2.3. Water Transfer System

Filling the basin to the maximum water level of 0.6 m (i.e., 0.8 m in the deep section) takes between 2- and 4 hours, depending on the type of model constructed inside the basin. To obtain the maximum water level, 240 m^3 of water are required. The OWB is filled either through freshwater from the neighbouring inland waterway (MLK—Mittellandkanal) or by groundwater from an adjacent drain sump. To avoid disturbance due to critical biological and chemical composition or water temperatures, a multiparameter water quality probe is deployed for monitoring during the experiments. The OWB is designed to also accommodate experiments with seawater. Therefore, a highly durable flexible PVC water tank will be made available in the coming months to store seawater next to the OWB. Experiments with seawater have to be conducted in a closed system to prevent corrosion of the general water transfer system at the existing infrastructure. Since the capacity of the flexible PVC water tank is limited, a water treatment can be installed to ensure the water quality during but also between the experiments.

2.4. Measuring Equipment and Data Acquisition

A multitude of measuring systems for the investigation of hydraulic and coastal engineering parameter is available in the OWB. Since the outdoor facility operates under real climate conditions, robust measuring devices and sensor equipment are installed permanently. In addition, a meteorological station, pressure sensors, a multiparameter water quality probe and velocimeters are deployed on a permanent basis. Additionally, 3D laser scans, ultrasonic sensors or hyperspectral measurements are conducted in episodic campaigns during experiments. A control room for data acquisition and wave generation are available in front of the OWB.

3. Pilot Project—Ecodike

The main objective of the pilot research project, named *Ecodike*, is to investigate how the ecological value of dikes and revetments as coastal protection structures can be enhanced. In collaboration with A. Graunke and N. Wrage-Mönnig (Grassland and Fodder Sciences, Faculty of Agriculture, University of Rostock) a test vegetation was developed for this project. An inventory of existing and new data of the vegetation types and their traits such as root depth, growth height or trampling resistance was carried out for the main natural ecosystems on the German coast. Suitable dike vegetation was identified on plant traits and properties that enhance erosion resistance. Multivariate statistics were used to classify and rank the main abiotic conditions for certain species or traits. In conclusion, species that are potential candidates for covering revetments and dikes were identified based on to their natural environment and were defined as different test vegetation.

In total six different test vegetation were designed, ranked by increasing ecological values (e.g., species richness and biodiversity) from test vegetation 1 to 6. Test vegetation 1 is a traditional grass mixture for dikes which contain only four grass species [36]. These number of grass species are substituted and increased systematically: test vegetation 2 contain 4 different species, while test vegetation 6 consist of 18 different herb and grass species. The ecosystem services offered by vegetation 6 are not limited to coastal protection, but also offer an increased quality of coastal habitats which promote a balanced ecosystem.

In this pilot project four of these six test vegetations were selected based on their suitability as grass cover for sea dikes. Physical model tests are conducted to evaluate the practical safety standards of these test vegetations and its application as revetments for sea dikes. An innovative monitoring approach, using full-waveform laser scans and hyperspectral measurements, is used to monitor the long-term vegetation development following seasonal variations in the growth phases under wave load. To identify the effects of wave load on the long-term vegetation development of the test vegetation, the seaside slope of a typical sea dike, containing a sand core and a 0.3 m clay layer, was constructed in the OWB. The model dike has a height of 1.5 m, a width of 14.2 m and a slope of 1:6 (see Figure 4A). According to the guidelines for experiments with real vegetation defined by Lara et al. 2016, original clay material for dike construction was transferred from the coast of the North Sea to Hannover to create natural conditions for the test vegetation. The model dike is divided into two main sections in order to investigate the vegetation development with and without stresses induced by wave loads. The two main sections are further divided into four subsections, each containing one of the four selected test vegetations. Within the last vegetation period in the overall dry year of 2018, grass revetments have been episodically exposed to wave load with wave heights ranging between 0.10 and 0.25 m and wave periods of 1 to 3 s for up to 7 to 10 h every second week. The tested grass mixtures consist of different types of unique grasses and herbs; and as such resemble a rather flexible, elastic vegetation coverage with only little structural stiffness on a 1:6 slope. Based on visual observations and preliminary measurements, no distinct differences in wave run-up and reflection between the four vegetation segments could be identified.

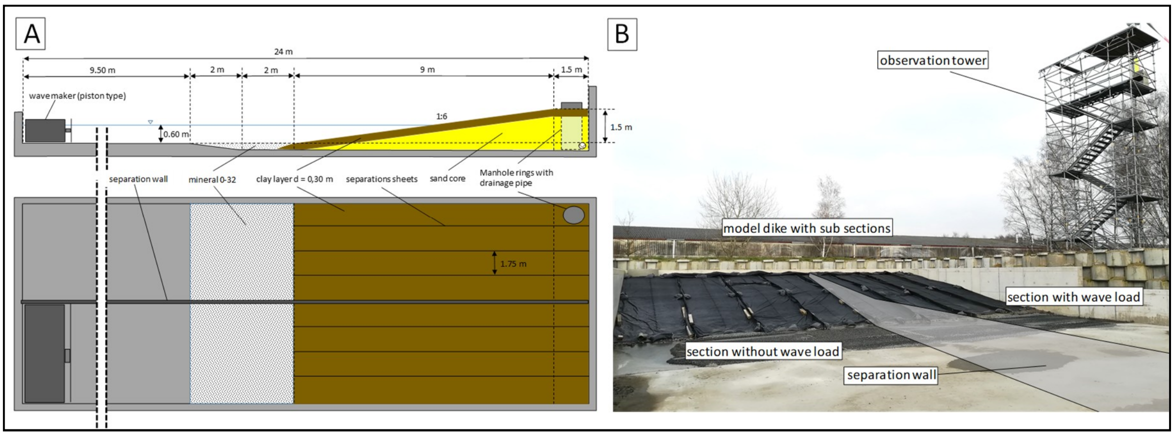

Figure 4. Model setup for the Ecodike project (**A**) and constructed model dike with two sections containing four subsections covered by protection-sheet during the winter months in February 2018 (**B**).

Duration of tests are divided into 10 min segments with 5 min breaks to avoid the development of any lateral patterns inside the basin. Additionally, the test vegetation is exposed to salt stress by artificially watering the dike with seawater to mimic environmental conditions on the North Sea. Furthermore, short test sets with regular waves are conducted to estimate wave run-up heights and maximum flow velocities on the dike for different stages in the anticipated lifetime of the target vegetation. After the vegetation period, the vegetation development (e.g., root depth and density, coverage index, species composition) and the resistance of the dike is quantified and analysed with shearing stress and pull-out tests. The combination of full-waveform laser scans and hyperspectral measurements, as well as the dike resistance parameter based on the measured vegetation development with and without wave load, lead to new insights in the long-term vegetation development. The specific adaptation processes of the vegetation to wave load will be identified to predict the associated long-term dike resistance. For example, an adaptation by increasing the subsurface biomass can lead to a decrease in the aerial biomass and positively influence their mechanical characteristics, thus possibly resulting in an increased dike resistance [19]. Thus, an innovative monitoring approach is developed based on the long-term vegetation development on the model dike. Figure 4B shows the prepared model dike covered by a sheet to protect the slope against erosion and settlement of unwanted vegetation during the winter months.

3.1. Preliminary Results—Erosion Resistance after One Vegetation Period

Preliminary insights during the initial phase after one vegetation period (i.e., March to September) indicate distinct differences between the test vegetations performance on the sea dike depending on the specific type of grass revetment of the test vegetation. Since the long-term test programme is not completed yet, only test vegetation 1 and 6 (i.e., with the lowest and the highest ecological value, respectively) are compared. Erosion only occurs at the dike sections of test vegetation 6 with high ecological values. Erosion depths have been measured at the wave impact zone about 0.2 times H_s below the still water level using a surface profilometer. The accumulated mean erosion depth after four wave load scenarios with a total duration of 20 hours and significant wave heights $H_s = 0.25$ m, are hardly significant for test vegetation 1. In contrast, test vegetation 6 experienced erosion of 3 cm on average. It should be noted that the test vegetation 6 has lower coverage indices due to a significantly lower seed per area ratio of 1 g/m^2 during the initial sowing process. Therefore, this test vegetation is more likely to show erosion compared to test vegetation 1 which has low species richness but significantly higher seed per area ratio of 18 g/m^2. A green value method was developed to differentiate between clay covered and uncovered by vegetation using RGB-images. Coverage indices were subsequently analysed at the wave impact zone. The mean coverage indices of the test vegetation 1 are 95% and for test vegetation 6 55%. Yet, it is expected that the coverage indices of test vegetation 6 are likely to increase in the upcoming seasonal vegetation growth phase with significant less erosion potential for any of the upcoming 20 h of wave load scenarios.

3.2. Outlook

After the test programme, the development of test vegetation with and without wave load is compared to better understand the limiting effects of wave load on the vegetation development and its ecosystem services (e.g., achievable coverage indices). Further tests of the different aspects of the achieved grass revetment resistance with and without wave load (e.g., shearing strength, pull-out tests and root depth and density) will help to understand the long-term development of the ecosystem service of the grass revetment. These measurements are conducted after completing the test programme to avoid disturbing the vegetation development. The initial damages created by conducting the grass revetment resistance measurements are likely to initiate erosion development [37,38].

4. Conclusions

The construction and the ongoing development of the new OWB enables new and innovative ways to investigate green coastal infrastructures with ecosystem services. The long-term experiments are extending the current knowledge on the long-term development of the ecosystem services while leading towards more ecologically friendly and sustainable coastal protection measures. The pilot research project provides first insights into the long-term development of the ecosystem services of different grass revetments (see Section 3). By focusing on the resistance and the ecological value of these grass mixtures, the compatibility of a high ecological value and safety standard of sea dikes are investigated. Future research considering the complex interactions between ecological and engineering aspects of the coastal infrastructure will help to develop reliable and practical design guidelines. The performance and design of green coastal infrastructures will be addressed in future projects by enhancing the state of the art for green coastal infrastructures to improve the understanding of the long-term development of nature-based, sustainable solutions. The upcoming projects can be used to enhance the knowledge of a multitude of issues resulting from the ecosystem-based coastal solutions. Long-term physical model tests under controlled boundary conditions will be used to identify differences in adaptation of vegetations to hydraulic stresses.

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