DuneFront

Deliverable 12.2

April 2026

Physical modelling of the German Demonstrator

Focus: vegetation influence on dune erosion

Deliverable 12.2 (D12.2)

Deliverable information

Title	Physical modelling of the German Demonstrator
Deliverable number	D12.2
WP number	12
Author(s)	Oliver Lojek(TUBS), Constantin Schweiger (TUBS),
Lead beneficiary	TUBS
Contributors	TU Berlin, UGhent
Type	Report
Dissemination level	Public
How to cite	Lojek O., Schweiger C., (2026).Physical modelling of the German Demonstrator, Version 1.0, DuneFront Project Deliverable 12.2, Technische Universität Braunschweig.

Versioning and contribution history

Version	Date	Authors (Institution)	Notes
Version 0.1	21/04/2026	Oliver Lojek (TUBS), Constantin Schweiger (TUBS)	Version to be checked and approved by DuneFront consortium
Version 1.0	01/05/2025	Oliver Lojek (TUBS), Constantin Schweiger (TUBS)	Final version approved by all Beneficiaries

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Cover page

This report is the first deliverable of work package 12 Coastal protection functioning (D12.2 Physical modelling of the German Demonstrator) in the DuneFront project. DuneFront focuses on better understanding dune-dike hybrid Nature-based Solutions (DD-hybrid NbS) to create sustainable, inclusive, and visually appealing coastal management infrastructure. These innovative solutions aim to integrate biodiversity while addressing significant socio-economic challenges along Europe's densely populated coasts. By studying existing hybrid NbS, this report lays the groundwork for better understanding the design aspects of these systems.

The primary objective of this report is to present results from a physical laboratory campaign involving live bed conditions (erodible sediment bed) in combination with living plants exposed to wave loads in a scaled physical experiment in a wave flume.

The DuneFront project considers 12 Demonstrators across six countries - Portugal, France, Belgium, the Netherlands, Germany, and Sweden – given the complexity and physical effort attached to physical models a single demonstrator site was modelled.

This compilation presents results obtained regarding the influence of vegetation on wave induced erosion of dunes of the select demonstrator. To this regard a total of nine (9) DuneCrates™ was conceptualized and set up, containing the seaward slope and crest of a dune from the German demonstrator Sankt Peter-Ording. Six (6) out of the DuneCrates™ were prepared with live marram gras vegetation and curated outside to mimic/consider environmental influences through wind, rain, sun and eventually snow and froist.

This report will be complemented by deliverables D12.1 and D12.3 contributing physical laboratory results from different demonstrator sites.

In general, this report provides an overview of the model setup and initial results regarding erosion influenced by varying degrees of vegetation cover and planting strategy. Complimentary reports D12.1 and D12.3 will advance the understanding of the simulated demonstrator sites by focusing on other details and.

Table of Content

List of Figures

List of Tables

List of abbreviations

Abbreviation	Explanation
DD	Dune-Dike
DD-Hybrid	Dune Dike-Hybrid
NbS	Nature based Solution
GIS	Geo-Information-System
WP	Work Package
RBMPs	River Basin Management Plans
WFD	Water Framework Directive
PoM	Programs of Management
KTM	key types of measures
NUTS	nomenclature of territorial units for statistics
APSFRs	Assessment of potential significant flood risk
RBD	river basin districts
PRFA	preliminary flood risk assessment
EFAS	European Flood Awareness System
EMODnet	European Marine Observation and Data Network
TWL	total water level
ECFAS	European Coastal Flood Awareness System
RI	Return interval
BSS	Brier-Skill-Score
TLS	Terrestrial Laser Scanner
DC	DuneCrate

1. Introduction

Overview of work package 12.2 (WP12 – Coastal protection functioning)

The overarching goal of work package 12 consists in conducting physical model experiments in hydraulic laboratories setting up models of select demonstrator sites. The Workpackage 12.2 “Physical modelling of the German Demonstrator” aims at conducting a physical laboratory campaign in a wave flume utilizing a scaled model of the German demonstrator Sankt Peter-Ording on the North Sea.

1.1 Tasks of work package 12

The objective of the first task (Task 12.1) is the investigation of different dike-in-front-of-dune configurations at the Dutch coast. Physical experiments have been conducted to investigate influences of different model configurations on for example over wash volumes using a fixed bed model.

The objectives for the second task (Task 12.2), this report, within the work package focus on using live bed conditions (sand) in combination with live vegetation (marram gras) within a wave flume model to investigate potential influences on dune erosion under storm surge wave conditions.

The objectives of the third task (Task 12.3) are the investigation of storm surge induced erosion on beach and dune configurations for the Belgian coast employing live bed conditions (sand) and variable slopes.

1.2 Milestones and Deliverables of work package 12

The key milestone (M12.2) involves the preparation and curation of scaled dune models with live vegetation on them. This milestone has been met.

The deliverables include:

- **Deliverable D12.1** Physical model campaign conducted by TU Delft for the Dutch Demonstrator in a wave flume. Measurements focus on hydrodynamics for wave loads and over wash.

- **Deliverable D12.2:** (This report) Physical model campaign conducted by the TU Braunschweig for the German demonstrator in a wave flume. Measurements focus on morphodynamics for dune erosion and hydrodynamics for wave loads.

- **Deliverable D12.3:** Physical model campaign conducted by Vlanders Hydraulics for the Belgian demonstrator in a newly built wave flume. Measurements focus on morphodynamics for dune erosion and hydrodynamics for wave loads and over wash.

- **Deliverable D12.**4: Validation of numerical models is to be carried out using the physical model data as calibration data base.

- **Deliverable D12.**5: Validated numerical models shall be used for a wider range of boundary conditions and dune and dike geometries to expand/project possible impacts and to find suitable solutions for individual sites.

1.3 Aims and objectives of this report

The main objective of this report is to present the numerical demonstrator models setups for XBeach and AeoLiS and achieved initial results.

2. Physical model of the German Demonstrator

St. Peter Ording is located at the Eiderstedt peninsula located in North Frisian Wadden Sea in Germany (Figure 1). The demonstrator is characterized by a broad system of multiple dikes and a natural grey dune system. The northern land protection dike, situated at an elevation of 8 m above mean sea level (amsl), serves as the primary line of defense. To the south of the dune system, a regional dike with a tar surface layer provides supplementary protection at an elevation of 6.4 m (amsl). A middle dike, situated behind both the dune system and the regional dike, serves as a secondary line of defence. The natural grey dune system, which varies in height from 6 to 16.5 m (amsl), occupies the space between the northern and southern dikes, thereby enhancing the overall coastal protection by providing a resilient, multifunctional barrier against storm surges and flooding.

Figure 1: Aerial phtoto showing St. Peter-Ording located at the Eiderstedt peninsula in the North Frisian Wadden Sea including grey & green coastal infrastructure (Photograph by Martin Stock)

2.1 Methods

2.1.1 Dune Model

A representative beach and dune profile has been selected from the coastal demonstrator site drawing on digital terrain model (DTM) data covering multiple decades (Mehrtens et al., 2023). The transect has been placed in collaboration with the coastal protection agency of Schleswig-Holstein, the federal state in which the demonstrator is located. Correspondingly, the transect represents one of the lower points within the beach and dune system, following the reasoning that in case a storm surge would breach the natural flood defense the dune provides, it would most likely happen along a transect, where the main grey dune called Maleens Knoll, does not reach its maximum of 16.5 m (asml) but a comparably low elevation of 8.0 m (asml).

The transect is shown in Figure 2, based on federal survey data from 2015. The average beach elevation reaches 2.0 m (amsl), a foredune chain rises between 200-300 m in front of the main dune up to 11.5 m (asml) in some locations (Mehrtens et al., 2023). Comparing Figure 1 one can see, that between the foredune chain and the main grey dune an extensive salt marsh lagoon has developed.

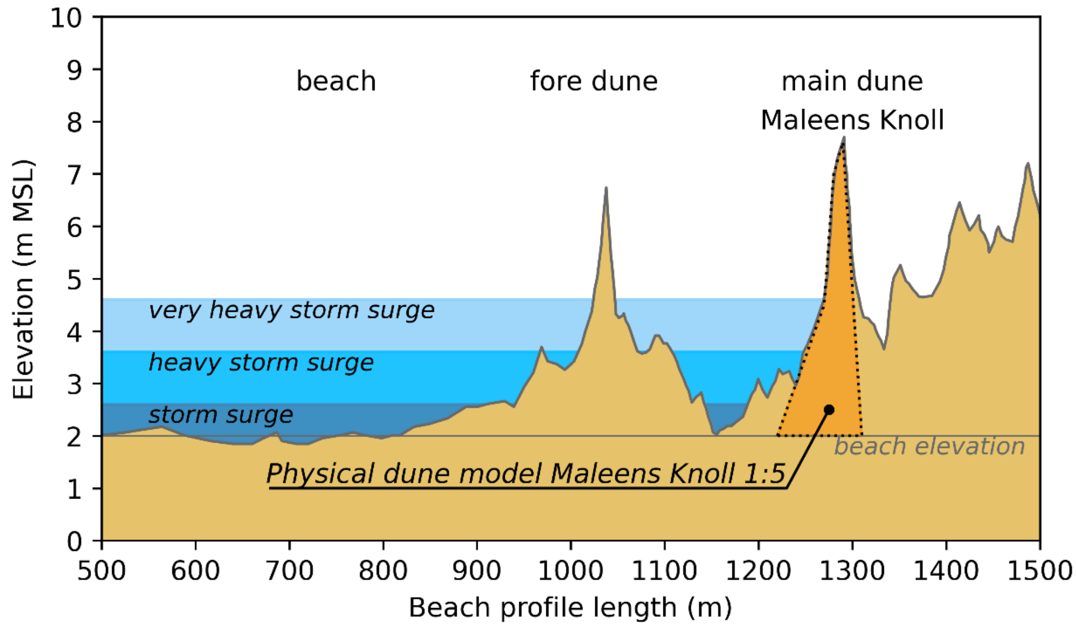

Figure 2: Beach and dune profile for the German demonstrator model

For the demonstrator model the main dune only was considered. This approach is based on the fact that the foredune chain presently features multiple breaches, that allow storm surges to infiltrate the area between the foredune and main dune. The effect of the foredune has been investigated regarding its volume, elevation and distance from the main dune, as all these parameters change along the foredune chain at the demonstrator. Physical and numerical results on this investigation are found in an open access publication (Schweiger et al. 2026).

The wave flume used for Work package 12.2 at the Leichtweiß-Institute for Hydraulic Engineering is 90 m long, 1.5 m deep and 1.0 m wide. It features a VTI wave maker from 2022 operated with AwaSyS v7 capable of generating significant wave heights of up to 0.4 m (Aalborg University 2023).

2.1.2 DuneCrates

The work package specified that the model was to feature a live bed (sand) which would be eroded by the waves and live plants (marram gras).

Live bed conditions are inherently difficult to scale and setup, as they include a lot of physical effort, given after each experimental run the sand has been eroded and moved and has to be reprofiled into the original model geometry for the ensuing experimental run.

The presence of live vegetation in the model precluded a setup inside the wave flume alone, as the either plants would have to be planted on short notice for every experimental run or the facility would be blocked for months, as the vegetation grows inside the flume on the live bed, provided the lighting conditions are conducive.

In order to mitigate this challenge, novel DuneCrates (Figure 3) were designed, which functioned as large dune planting crates. These crates were designed with computer aided design (CAD) and manufactured by a steel construction company in Braunschweig, Germany for the work package 12.3. The DuneCrate has the dimensions 2.5 m by 0.975 m by 1.10 m (LxWxH). The dimensions allow for the upper slope and crest of the dune profile to be contained. The wall thickness of the DuneCrate is 5 mm thick steel, the bottom plate features perforations to avoid water logging. The bottom has 5 rows of pick-up points designed for fork lifts etc. to move it easily. The overall size was designed so that the DuneCrate fits inside the 1 m wave flume and can still be lifted and moved by the laboratory's portal crane, which has a total lift capacity of 3.5 t. Empty DuneCrate weight 379 kg, with sand ~2.9-3.3 t (moisture dependent). The front latch can be removed vertically, to allow the frontal dune slope to be eroded by waves, once placed inside the wave flume. In total 1 prototype and 8 refined DuneCrates were manufactured for Work Package 12.3.

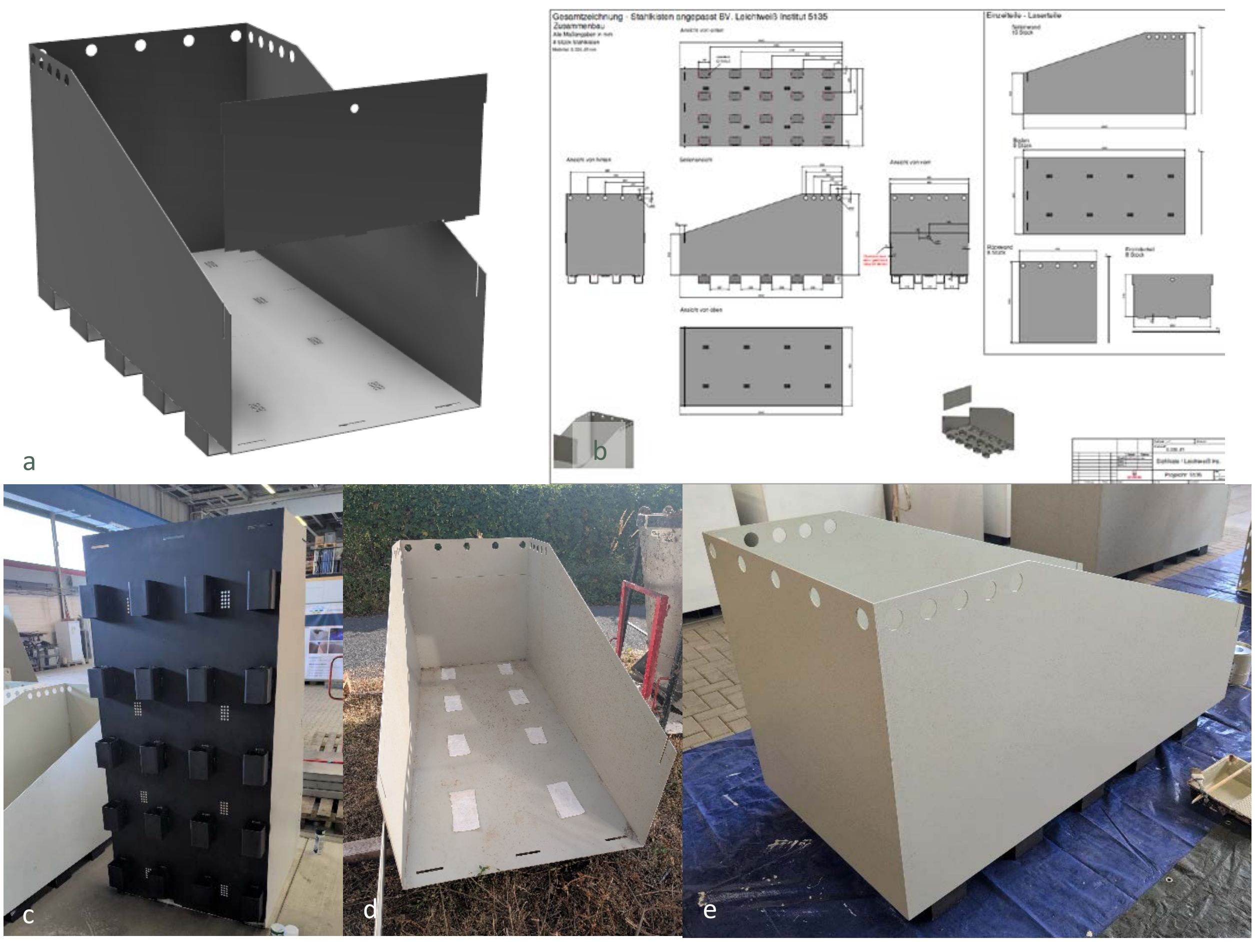

Figure 3: a) 3D Rendering of DuneCrate b) CAD Plan of DuneCrate c) Bottom panel painted d) Inside painted and perforation covered with filter layers to avoid sand loss e) DuneCrate painted

The DuneCrates were painted to prevent corrosion and setup outside the hydraulic lab to allow for environmental influences and provide sunlight for the vegetation to grow. Out of the 9 DuneCrates, 3 were prepared with sand only to serve as reference cases and six were prepared with live vegetation following different approaches (Figure 4).

Figure 4: a) Initial setup of the dune crates outside the hydraulic lab with final dune model profile line in black marked b) final stage of top planted DuneCrates

Starting out, all DuneCrates were filled with 1.0 m³ as a starting point (Figure 4a). DuneCrates 01, 02 and 03 were filled with sand only and featured no plants. DuneCrate 01 was filled in one go to the pre-defined dune model profile line (black in Figure 4a). DuneCrates 02 and 03 were filled incrementally elevating the dune crest 0.05 cm every two weeks. Similar approaches were chosen for DuneCrates 04, 05 and 06 – these were all filled to the pre-defined dune profile line in one go at the initial setup date and the vegetation was top planted, meaning the saplings were planted from the top into the dune model. Following a staggered 3-2-3-2-3 placement, 13 (thirteen) saplings were planted. DuneCrates 07-09 also featured 13 saplings in a matching, staggered arrangement. However, DuneCrates 07-09 were incrementally elevated matching the rate of DuneCrates 02 and 03 with 0.05 m every two weeks.

These different approaches were chosen to potentially elucidate the influence of "built" physical models, which are usually setup inside a wave flume by hand and compacted to a varying degree. This approach is mimicked by DuneCrate 01. The incremental layering of the DuneCrates 08, 09 (sand only) and 05-07 (sand + vegetation) is emulating the natural built-up of dunes, which are fed by aeolian sediment transport settling on top of the dune, resulting in an overall volume increase and crest elevation. The filled and top planted DuneCrates 02-04 represent strategies often found in federal coastal protection agencies, when they re-profile or nourish dunes after storm surge seasons. These are constructed to a pre-defined profile elevation and then top-planted in a staggered array. The number of plants per m² is oriented at a federal construction definition (NLWKN 2006).

Table 1: Compilation of DuneCrate model setups

Name	Accr.	Contents
DuneCrate 01	DC01	Sand only, filled in one
DuneCrate 02	DC02	Sand and plants, filled in one, staggered vegetation rows, 13 saplings
DuneCrate 03	DC03	Sand and plants, filled in one, staggered vegetation rows, 13 saplings
DuneCrate 04	DC04	Sand and plants, filled in one, staggered vegetation rows, 13 saplings

DuneCrate 05	DC05	Sand and plants, filled incrementally, staggered vegetation rows, 13 saplings
DuneCrate 06	DC06	Sand and plants, filled incrementally, staggered vegetation rows, 13 saplings
DuneCrate 07	DC07	Sand and plants, filled incrementally, staggered vegetation rows, 13 saplings
DuneCrate 08	DC08	Sand only, incrementally layered
DuneCrate 09	DC09	Sand only, incrementally layered

2.1.3 Model setup

Given the DTM based transect, the model was scaled using Froude similarity scaling (Hughes 1993). The largest possible model scale that fits in the facility features a scale of 1:5, which was implemented. This resulted in an overall model length of 12.65 m and a total dune crest height of 1.05 m. To allow the plants to grow, the DuneCrates were conceptualized and prepared outside the hydraulic lab to provide sunshine, rain and wind for the vegetation to develop more naturally. The DuneCrates were moved inside the lab, once the incrementally layered DuneCrates 02, 03 and 07-09 all reached the same elevation as the others. For this an external crane company was contracted, as the individual DuneCrates were too heavy for the on-site available forklifts (Figure 5).

Figure 5: a) DuneCrates November 2025 b) DuneCrates January 2026 with snow cover c) Moving of DuneCrates by boom truck d) Unloading of DuneCrates inside the hydraulics lab e) DuneCrates thawed and with painted vegetation for tracing of plants during erosion experiments

The wave flume model was designed in such a way that the flume floor resembles the beach elevation at the German demonstrator in Sankt Peter-Ording, reaching 2 m (asml) in real life. Above the flume floor, the main dune with its dune toe was erected out of sand. The sand was chosen based on field data from Sankt Peter-Ording, which was then scaled down using the Dean parameter (Dean and Dalrymple 2002) to ensure the sinking velocity matches. The overall sediment grain size could not be scaled down enough, as otherwise the material would be cohesive and act like clay and not sand and render not suitable for the experiment. This shortcoming is well known in hydraulic experiments with live bed conditions. However, given that rather large scale of 1:5 the impact is smaller, compared with model scales like 1:20. The median grain size (d_{50} = 0.19 mm with a uniformity coefficient of = 1.06) was selected by optimizing the model–prototype fit in terms of two key dimensionless groups: Reynold's number $Re = w \cdot D^{*} \cdot \nu^{-1}$ and the Dean number $D = H_b \cdot (w \cdot T)^{-1}$, where w is the sediment settling velocity, D^{*} the specific grain diameter, ν the kinematic viscosity of water, H_b the wave breaker height, T and the wave period (Dean and Dalrymple 2002).

The model construction inside the wave flume used 3.1 m³ for the beach and dune toe area in front of the DuneCrate latch. The volume below the location of the DuneCrates was built up with stone to form a solid and level base for the DuneCrates to rest upon. The dune toe area was confined from being washed underneath by a sheet pile wall installed between the lip of the DuneCrate and the flume floor (Figure 6). On the side of the DuneCrates a rubber seal was installed to minimize leakage.

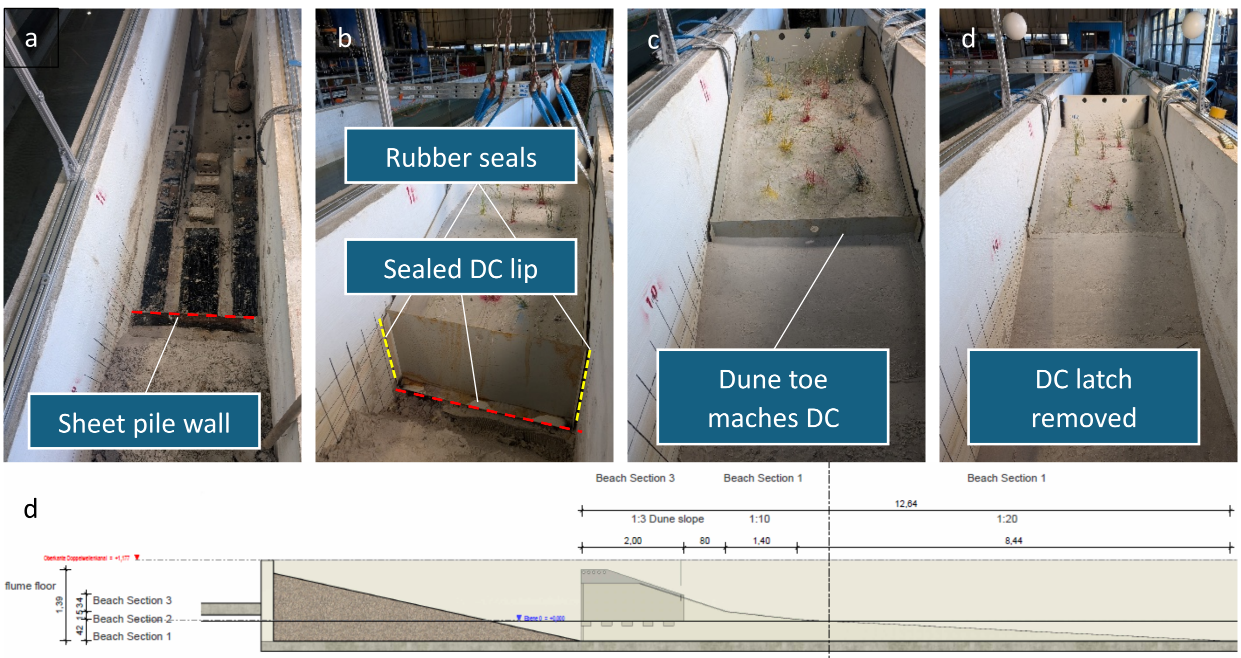

Figure 6: a) Foundation for DuneCrates with sheet pile wall b) lowered DC07 on foundation sealed lip by sheet pile wall c) Installed dune to matches profile inside DC07 d) removed DC07 latch e) CAD sketch of model setup

2.1.4 Boundary conditions

Overall, the model experiments were conducted aiming for collision regime conditions (Asbury H. Sallenger, JR. 2000), as overwash was not possible to model due to the solid steel backplate of the DuneCrates, which would result in non-natural reflection and unusable data.

The hydrodynamic boundary conditions comprise a storm surge resembling an event with a 200-year return period for the German demonstrator site. Scaled down to 1:5 for the model setup this results in a water level of 0.66 m, a significant wave height of 0.2 m and a peak wave period of 3.3 s. Total duration of the storm surge conditions amounts to 134 min model time (298 min real time ~ 5hrs) segmented into 4 individual wave bursts (WB) lasting WB01 = 12 min, WB02 = 24 min, WB03 = 35 min and WB04 = 63 min, respectively. The segmentation was done to allow for bathymetric assessment of the area underwater by echosounders, which would interfere with wave trains during the experiment, so the waves were paused for these measurements, but the water was not drained. The incrementally increasing duration of the WBs was chosen based on the rate of morphodynamic changes in the model, happening more rapidly at the beginning and developing a more stable Bruun's profile towards the end of the experiment (Bruun 1954).

A second storm surge condition was prepared with elevated water levels of 0.76 m and similar wave conditions, to be tested on select DuneCrates after the initial storm was completed. The reasoning for this is based on real world conditions, where multiple storm surge events make landfall during a single winter, thereby eroding the beach and dune system at Sankt Peter-Ording. The experimental setup was designed to mimic these conditions more realistically. The elevated water level results in an event with a 200-year return period still but projected into the year 2100 with elevated water levels due to sea level rise (SLR).

3. Results

In total 1.05 TB of data was recorded during the nine (9) experiments with the DuneCrates. Results include ultrasonic wave gauge data from six (6) gauges. Two optical back scatter (OBS) sensors detecting turbidity. An acoustic doppler profiler for wave celerity. An acoustic doppler velocity profiler (ADVP) measuring 3D velocity and turbidity. Two cameras, one side looking, one top down. A solid state LiDaR cube measuring 3D distance for dune erosion during the experiment. A terrestrial laser scanner for high accuracy 3D surface assessment. The data was sampled with 50For this report, results from the ultrasonic wave gauges and the ADVP will be presented for evaluating the hydrodynamics and the terrestrial laser scanner data. Regarding morphodynamics, images from the cameras will be presented. The other systems were operated to collect back-up data in case the primary systems fail. The data will also be used to further refine numerical models operated in WP11.

3.1 Waves

Waves were recorded with an ultrasonic Ultralab model HF-58 by General Acoustics GmbH from Kiel, Germany. The system allows for up to 8 wave gauges to be operated in parallel and up to 16 for very steep or breaking waves (Figure 7). For this campaign 6 gauges of type USS10 were installed featuring a measurement range of 1.2 m. Three were located offshore (Figure 8) from the model, which are used for the ensuing hydrodynamic and wave reflection analysis. Another three were installed on a movable trolley (Figure 9), which was positioned on the beach during the wave experiments. This data is not suitable for a wave and reflection analysis, due to the underlaying slope and water depth constantly changing. They were placed here to assess nearshore wave transformation processes for the purpose of calibrating numerical models such as XBeach.

Figure 7: Ultralab HF-58 setup at 1 m wave flume

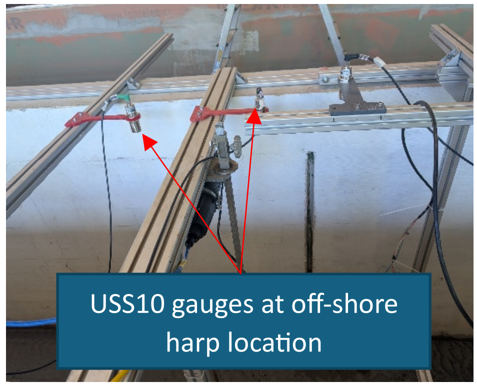

Figure 8: Offshore wave gauge harp in front of data acquisition setup

Figure 9: Movable trolley with gauges

The wave data has been processed and evaluated using WaveLab (Aalborg University 2026) allowing for standardized Zero-Up crossing analysis as well as spectral analysis of provided wave elevation time series. For demonstration purposes Table 2 showcases the statistical analysis obtained for various wave parameters from the measured elevation time series. A significant wave height of 0.2 m was implemented as boundary condition into Awasys (Aalborg University 2023) for the wave maker. The analysis of the gauge data reveals an overall reduction of the incident significant wave height at the offshore wave gauge harp between -6.7% and -8.1% for all wave bursts across all experiments. The only exception presents wave burst 1, which shows a loss of -11.5% on average for all experiments. Overall, the total number of waves as well as the energy losses calculated for $H^{1/3}$ show consistent values across the wave bursts between the experiments.

Table 2: WAVELAB analysis for USS10 wave gauges 1-3 located on the beach and 4-6 located offshore from the DuneCrate model for DuneCrate 01 exposed to storm A boundary conditions.

	Spectral Analysis						Zero Up Crossing							
	Hm0 (m)	Tp(s)	Tm_10 (s)	Tm01 (s)	meanEta (m)		H 1/3 (m)	Hmax (m)	Hm (m)	T 1/3 (s)	Tm (s)	Number of Waves	Inserted Hs (m) Awasys	Losses in H 1/3 (%)
DC01_StormA														
WaveBurst_1														
USS_01	0,2036	3,1203	2,9381	1,6614	-4,02E-17		0,2303	0,7564	0,1358	2,7808	2,3184	299	0,2	-11,5
USS_02	0,2077	3,2567	2,9213	1,9352	-6,02E-17		0,2035	0,3707	0,1022	2,8433	1,8751	377	0,2	
USS_03	0,2072	3,2672	3,0323	2,163	-3,26E-17		0,2061	0,4051	0,1173	2,8945	2,2617	313	0,2	
USS_04	0,176	3,2233	3,2512	2,4203	6,47E-17		0,1745	0,275	0,1067	2,7857	2,3563	299	0,2	
USS_05	0,1772	3,216	3,2507	2,4116	5,40E-17		0,1754	0,2648	0,1064	2,8306	2,3312	301	0,2	
USS_06	0,1847	3,1926	3,2285	2,4592	-2,45E-17		0,1809	0,284	0,1099	2,799	2,3572	299	0,2	
DC01_StormA														
WaveBurst_2														
USS_01	0,2184	3,2108	3,0099	1,7464	2,33E-16		0,2467	0,544	0,1443	2,9189	2,3885	593	0,2	-8,1
USS_02	0,2177	3,2992	3,0894	1,996	-8,94E-17		0,2308	0,452	0,1373	2,9377	2,4124	587	0,2	
USS_03	0,2059	3,2168	3,1938	2,1271	5,35E-18		0,2125	0,4085	0,1299	2,9402	2,4644	576	0,2	
USS_04	0,188	3,2016	3,1999	2,4041	-6,88E-17		0,1842	0,3018	0,1134	2,8899	2,369	599	0,2	
USS_05	0,1894	3,2073	3,1908	2,4186	5,46E-17		0,1834	0,2902	0,1116	2,8425	2,3105	614	0,2	
USS_06	0,189	3,2092	3,1909	2,4396	8,19E-17		0,1838	0,2978	0,1146	2,939	2,3922	593	0,2	

DC01_StormA														
WaveBurst_3														
USS_01	0,2258	3,2665	3,0586	1,7129	2,07E-16		0,2534	0,5955	0,1493	2,9184	2,4062	865	0,2	-7,4
USS_02	0,2108	3,3415	3,145	1,9983	5,70E-17		0,2268	0,4528	0,1313	2,9514	2,3617	881	0,2	
USS_03	0,1998	3,25	3,1723	2,1218	1,03E-16		0,2068	0,3757	0,1207	2,9367	2,2941	907	0,2	
USS_04	0,1921	3,2373	3,1551	2,4024	-4,15E-17		0,1812	0,3089	0,1034	2,8704	2,1839	968	0,2	
USS_05	0,1918	3,2387	3,1795	2,4241	-2,14E-16		0,1869	0,3348	0,1141	2,9145	2,3895	872	0,2	
USS_06	0,1925	3,2278	3,1637	2,4335	1,38E-16		0,1873	0,3649	0,1143	2,9071	2,3869	873	0,2	
DC01_StormA														
WaveBurst_4														
USS_01	0,2294	3,3005	3,0037	1,4293	5,29E-17		0,2648	0,8659	0,1574	2,9652	2,4394	1576	0,2	-7,6
USS_02	0,2144	3,3203	3,0751	1,8667	-1,90E-16		0,2299	0,7655	0,135	2,9747	2,3848	1611	0,2	
USS_03	0,1981	3,2485	3,1161	2,1248	-5,55E-17		0,2058	0,4368	0,1225	2,882	2,3431	1640	0,2	
USS_04	0,1915	3,1935	3,0953	2,3967	8,42E-17		0,1838	0,308	0,1138	2,8895	2,3563	1631	0,2	
USS_05	0,1919	3,1962	3,09	2,4032	-6,77E-18		0,1862	0,3114	0,116	2,8989	2,4155	1591	0,2	
USS_06	0,1906	3,1661	3,0847	2,4068	6,16E-18		0,1839	0,3489	0,1136	2,9072	2,3584	1630	0,2	

In addition to the statistical values calculated, Figure 10 to Figure 13 show the recorded surface elevation time series for the wave bursts 1-4 for wave gauge number 6 during the DuneCrate 01 experiment for storm condition A. The time series data was processed, so that the leading 50 seconds as well as the trailing 300 seconds were cut off for ensuing statistical evaluation in Wavelab.

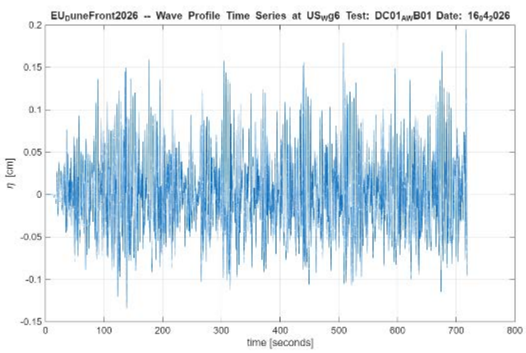

Figure 10: Water level elevation η in meter for ultrasonic wave gauge number 6 located offshore from the model for wave burst 01 storm A

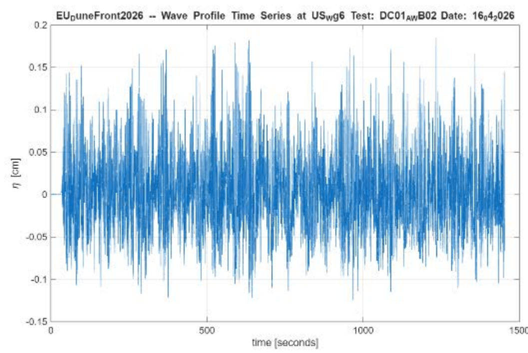

Figure 11: Water level elevation η in meter for ultrasonic wave gauge number 6 located offshore from the model for wave burst 02 storm A

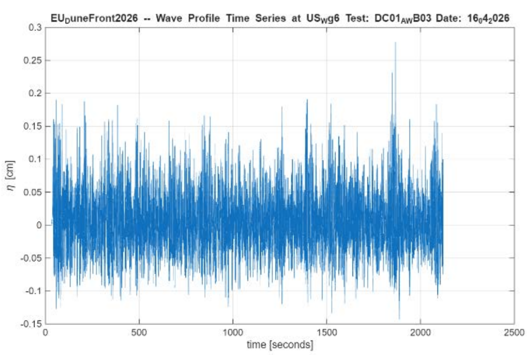

Figure 12: Water level elevation η in meter for ultrasonic wave gauge number 6 located offshore from the model for wave burst 03 storm A

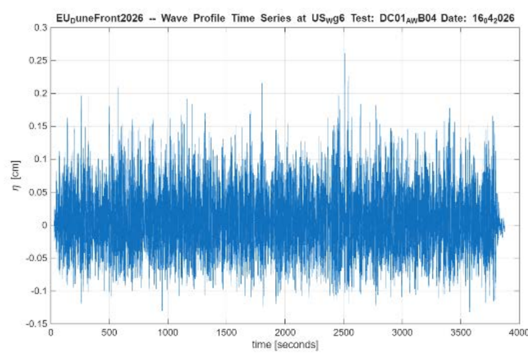

Figure 13: Water level elevation η in meter for ultrasonic wave gauge number 6 located offshore from the model for wave burst 04 storm A

The initial 50 seconds recorded are still water level and contain no waves, the trailing 300 seconds are the calm down period, during which the wave maker counter-acts the wave movements to generate quiescent water level conditions to avoid undesired impacts through re-reflection of waves on the morphodynamics.

This evaluation has been conducted for all experimental runs and shows consistent values. Given the same settings were used for Awasys to generate each wave burst, the sequence of waves generated by the machine is identical across the experiments. Slight variations in recorded signals exist, due to the beach and dune model reacting differently depending on the DuneCrate (sand only, vegetation, top-planted vs. buried). Nevertheless, the consistent wave energy loss and near identical number of detected waves per wave burst for all experiments renders the experiments comparable in terms of wave boundary conditions.

3.2 Morphodynamics

Morphodynamic response of the live bed beach and dune model with and without vegetation was assessed using a terrestrial laser scanner (TLS), model Faro type S+. The scanner was deployed before every experimental run and after (Figure 14). Per survey four scan positions were used and repeated after the storm had eroded the beach and dune model cumulating in 72 laser scan files. These were processed using the proprietary SCENE software (FARO 2019) provided by the manufacturer for the scanner in conjunction with reference globes on the model (Figure 15). For every DuneCrate a before (A) and after (B) scan were compiled, point clouds matched and clipped to exclude undesirable data from adjacent infrastructure. Subsequently, the point clouds for all experiments were matched on one coordinate system using Cloud Compare (Figure 16) for subsequent evaluation or morphodynamic impacts.

Figure 14: (left) Faro S+ scanner at the dune toe area (center) perspective towards wave maker (right) white reference globes positioned on the instrumentation frame arching across DuneCrate 05.

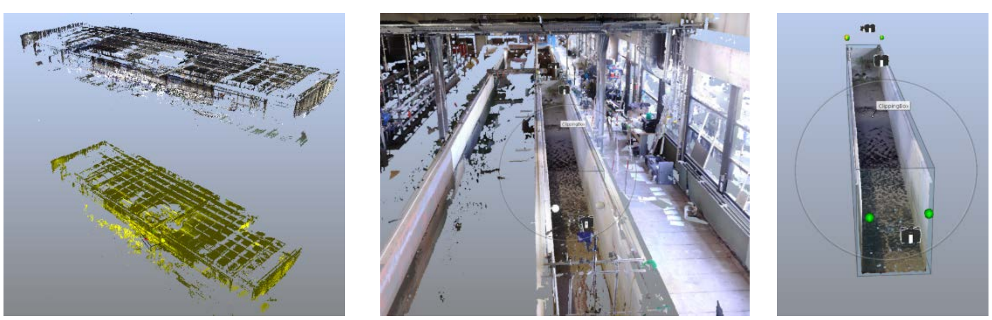

Figure 15: SCENE point cloud matching between scans (center) facility and bounding info (right) applied clipping box to filter for wave flume with dune model only for XYZ point cloud extraction.

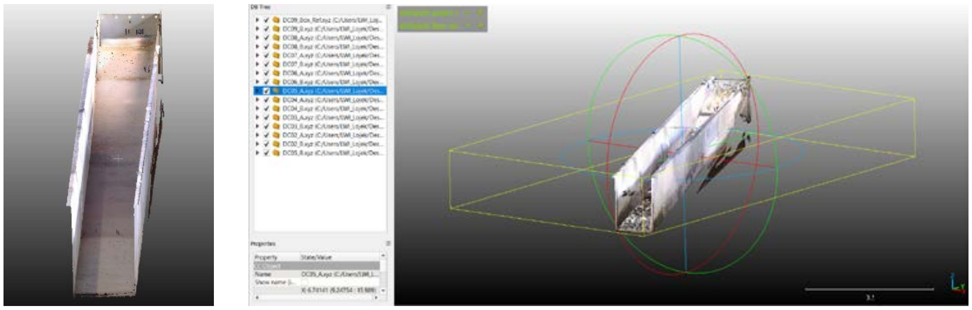

Figure 16: Cloud Compare software to match all XYZ point clouds for subsequent evaluation.

Quality statistics obtained from Cloud Compare (CloudCompareProject 2026) for all DuneCrate point clouds referenced to one global system resulted in a maximum error of 0.12 mm rendering the XYZ data accurate for further use.

The XYZ point clouds per DuneCrate experiment consistent of a pre- and post TLS scan, these were individually imported with Python Visual Code (Microsoft 2026) and processed. Data was averaged in cross flume direction and interpolated on a uniform X-vector running along the flume floor positioning the start point at the dune toe = 0.0 m and the end at the backwall of the DuneCrate = 12.65 m. The cross flume averaged values were linearly interpolated onto this vector for all experiments to obtain a unified reference coordinate system. Afterwards the pre- and post-scans were plotted and changes in elevation between the lines shaded for erosion (red) and accumulation (yellow). Results for all crates are shown in Figure 17 - Figure 25. The range where the DuneCrate was positioned is shaded in light grey.

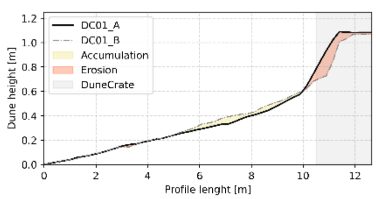

Figure 17: Erosion of DC01

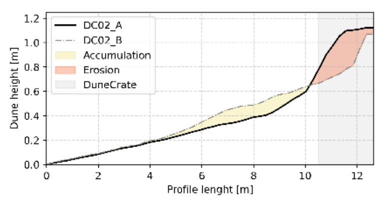

Figure 18: Erosion of DC02

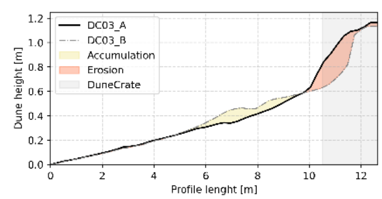

Figure 19: Erosion of DC03

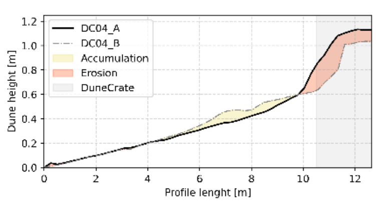

Figure 20: Erosion of DC04

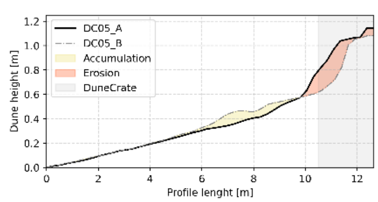

Figure 21: Erosion of DC05

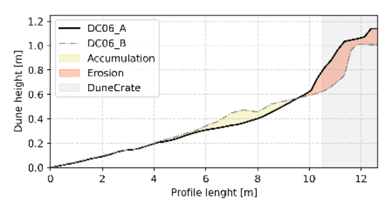

Figure 22: Erosion of DC06

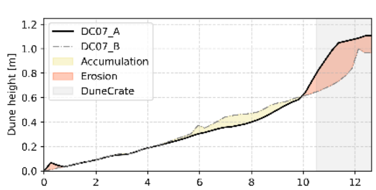

Figure 23: Erosion of DC07

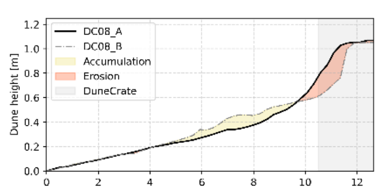

Figure 24: Erosion of DC08

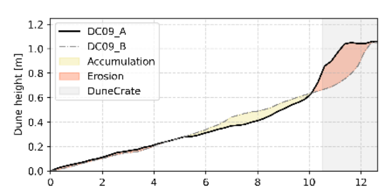

Figure 25: Erosion of DC09

Based on the evaluation scripts, the shaded area sizes were calculated and multiplied by the flume width of 1 m to arrive at volume changes. The results for all DuneCrate experiments are listed in Table 3.

Table 3: Morphodynamic response of DuneCrate models assessed through TLS scans evaluated in Python

DuneCrate [-]	Erosion [m³]	Accretion [m³]	Cum. Sed./Ero. [m³]	Net change [m³]	Model type
DC01	0.21	0.16	0.36	-0.05	Sand*
DC02	0.46	0.48	0.94	-0.02	Sand, top-planted
DC03	0.38	0.24	0.62	-0.14	Sand, top-planted
DC04	0.45	0.25	0.70	-0.19	Sand, top-planted
DC05	0.33	0.24	0.57	-0.09	Sand, vegetation buried
DC06	0.39	0.27	0.66	-0.13	Sand, vegetation buried
DC07	0.52	0.27	0.79	-0.25	Sand, vegetation buried
DC08	0.31	0.31	0.62	-0.00	Sand, layered
DC09	0.45	0.25	0.70	-0.20	Sand, layered

The tabulated values show that the erosion volumes for DC02-DC04 with the top planted setup are the highest one across all experiments averaging in at 0.43 m³/m erosion, followed by the incrementally buried setup from DC6-DC07 with 0.41 m³/m erosion and DC07 showing the highest single value with 0.52 m³/m, trailed by the layered sand setup in DC08 & DC09 with 0.38 m³/m. The value obtained for DC01 with 0.21 m³/m erosion is the lowest measured.

4. Conclusions

Nine novel DuneCrates were conceptualized and manufactured for the D12.3 experimental campaign to curate live vegetation in live bed conditions outside the lab to allow for environmental influences like sunlight and rain for the vegetation to prosper and develop.

Different setups were realized for the DuneCrates, from sand only filled in one go (DC01), via incrementally layered sand built up of bare dunes (DC08 & DC09) to top-planted (DC02-DC04) and incrementally buried vegetated ones (DC05-DC07). Each DuneCrate was successfully prepared over the course of multiple months and transported inside the lab in January 2026. Sequential installation and testing of the individual DuneCrates lasted from mid-February 2026 to early April 2026.

A comprehensive experimental frame work was designed and executed, applying storm boundary conditions to the dune model setup in a wave flume. Data acquisition systems were deployed to assess and measure various quantities before, during and after each experiment, culminating in a total of >1 TB data to be processed. This report elucidates the wave boundary conditions used as well as the corresponding morphodynamic response of the dune models through 3D laser scans.

Wave time series data was analyzed using Wavelab. Results show a very consistent boundary conditions with no deviations, rendering the individual experiments inter-comparable, given they have all been exposed to near-exact identical wave sequences and elevations.

Morphodynamic response to the boundary conditions was assessed using pre- and post-storm laser scan data of the dune model without water in the flume. A consistent processing of the data with three different software resulted in dune erosion volumes. The obtained results show that the top-planted DuneCrates eroded the most during the experiments, while the incrementally buried ones eroded slightly less. Lower erosion values were obtained for the layered sand only DuneCrates and the lowest one was detected for the DuneCrate with sand only, which was filled in one heap.

These results indicate that the presence of vegetation increases the amount of erosion given identical wave boundary conditions. Similar findings have been reported for extreme storm conditions (Feagin et al. 2023). However, other studies indicate a contrary influence of vegetation dune erosion (Kosmalla et al. 2026).

Given the comparably short time period from September 2025 to January 2026 during which the vegetation was given the chance to grow and establish root systems inside the DuneCrates, it is questionable if this has happened to a satisfactory degree. Especially, since vegetation such as marram gras, enters a dormant phase during winter, exactly when the experiment was prepared.

Correspondingly, the experiment will have to be repeated in parts to elucidate the influence of seasonal environmental parameters such as temperature on plant and root development.

5. Publication bibliography

Aalborg University (2023): AWASYS. Wave generation and active absorption software. Version 7. 9220 Aalborg East - Denmark: Aalbord University. Available online at https://www.en.build.aau.dk/for-the-building-industry/hydrosoft/awasys, checked on 4/15/2026.

Aalborg University (2026): WAVELAB. Data acquisition and wave analysis software. Version 2026. 9220 Aalborg East - Denmark: Aalbord University. Available online at https://www.en.build.aau.dk/for-the-building-industry/hydrosoft/wavelab, checked on 4/15/2026.

Asbury H. Sallenger, JR. (2000): Storm Impact Scale for Barrier Islands. In *Journal of Coastal Research* 16 (3), pp. 890–895. Available online at http://www.jstor.org/stable/4300099, checked on 4/30/2026.

Bruun, P. (1954): Coastal erosion and the development of beach profiles.,. In *In Beach Erosion Board Technical Memo* No. 44.

CloudCompareProject (2026): Cloud Compare. 3D point cloud and mesh processing software. Version 2026.1. global: CloudCompareProject. Available online at https://www.cloudcompare.org/, checked on 09/2025.

Dean, Robert G.; Dalrymple, Robert A. (2002): Coastal processes. With engineering applications. Cambridge UK, New York: Cambridge University Press.

FARO (2019): SCENE. Version 2019.7. Intel Core i7/i9/Xeon, 8 physische Kerne, 64 GB RAM, OpenGL 4.3,1 TB Solid State Drive + reguläre HDD,. 70825 Korntal-Münchingen, Germany: FARO. Available online at https://www.faro.com/de-DE/Products/Software/SCENE-Software, checked on 3/15/2026.

Feagin, Rusty A.; Innocenti, Rachel A.; Bond, Hailey; Wengrove, Meagan; Huff, Thomas P.; Lomonaco, Pedro et al. (2023): Does vegetation accelerate coastal dune erosion during extreme events? In *Science advances* 9 (24), eadg7135. DOI: 10.1126/sciadv.adg7135.

Hughes, Steven A. (1993): Physical models and laboratory techniques in coastal engineering. Singapore, River Edge NJ: World Scientific (Advanced series on ocean engineering, 7).

Kosmalla, Viktoria; Lojek, Oliver; Ahrenbeck, Lukas; Mehrtens, Björn; Schweiger, Constantin; Schürenkamp, David; Goseberg, Nils (2026): Vegetation effects on dune erosion under wave collision:

Influence of planting density, biomass distribution and arrangement in scaled experiments. In *Coastal Engineering* 204, p. 104899. DOI: 10.1016/j.coastaleng.2025.104899.

Microsoft (2026): Visual Code Studio. Version 1.118.0: Microsoft. Available online at https://code.visualstudio.com/, checked on 05/2025.

NLWKN (2006): Sicherung und Verstärkung der Schutzdüne vor dem Pirolatal auf Langeoog. Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz. Edited by NLWKN Betriebsstelle Norden-Norderney. Jahnstr. 1, 26506 Norden. Norden, Germany. Available online at https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.nlwkn.niedersachsen.de/download/22173/Broschuere_mit_Informationen_zum_Kuestenschutzprojekt_Pirolatal_auf_Langeoog.pdf, updated on 2006, checked on 9/10/2025.

Schweiger, Constantin; Lojek, Oliver; Bölker, Thea; Mehrtens, Björn; Schürenkamp, David; Goseberg, Nils (2026): Foredunes in Front of Secondary Dunes Exhibiting Strong Reduction Potential in Storm Wave Settings: A 2D Experimental and Numerical Study. In *JGR Earth Surface* 131 (4), Article e2025JF008756. DOI: 10.1029/2025JF008756.