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# A Full-Size Hybrid Dune Field Experiment: Design and First Results

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**Abstract.** Coastal defense strategies increasingly include hybrid dunes, which combine sandy dunes with hard structures. In the case of hybrid dunes, the sandy system and hard elements interact. Wave impact, reflection runup as well as dune erosion and scour are all being affected by both the hard elements and sandy parts. To better understand these interactions, we conducted a field experiment, with a hybrid dune setup to measure hydrodynamics and dune erosion during storms. The experiment setup contains four cross sections to compare the morphological development at a sandy dune (1), dike-in-dune (2), vertical wall-in-dune (3) and dike (4). The works took place in the winter of 2024/2025. The various storms that occurred caused strong erosion to the test setup. Preliminary results show that while the hard elements slowed down dune retreat behind them, the beach morphology in front remained remarkably similar. Erosion may have been governed by large-scale sediment availability in the system, beach elevation and hydrodynamics rather than by hard-soft interactions at the hybrid dune.

**Keywords:** Hybrid flood defense · green-gray infrastructure · hard-soft interaction · dune erosion · dike

## 1 Introduction

Hybrid dunes combine sandy dunes with hard structures and are increasingly being implemented for coastal flood protection. These hybrid dunes aim to combine the advantages of sandy dunes, such as space for nature and recreation, with those of structures like levees and dikes, such as predictable safety and erosion resistance. Sometimes, dunes have accreted naturally at manmade structures, similarly resulting in hybrid flood defense. Also, hybrid dunes can be formed when e.g. buildings are constructed in dunes for other means, as they unintendedly alter hydrodynamics and dune erosion during storms.

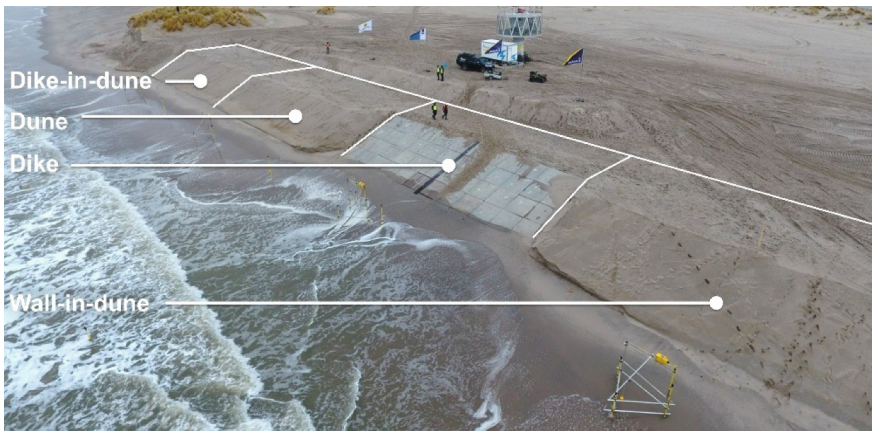
The stability of these hybrid dunes, also known as hybrid flood defense, is not only a function of the classical behavior of either individual hard or soft parts under

wave attack: complex feedback processes between dune morphology, wave action and structural stability start to play a role. In recent years, physical model experiments have been carried out to examine the hydrodynamics and sandy morphodynamics of a limited number of hybrid structures (e.g. Van Geer et al., 2009). However, these physical model experiments are often hampered by sediment scaling effects, and do not address crucial alongshore processes. Although these interactions are essential to properly design new hybrid dunes or evaluate the safety of existing ones, they remain poorly understood.

To gain knowledge and understanding on hybrid structures, we have developed a field experiment, where we measure the hydrodynamics and dune erosion during storms at an hybrid dune construction in the field. In this contribution, we will present the experimental setup, instrumentation and first results.

## 2 Methodology

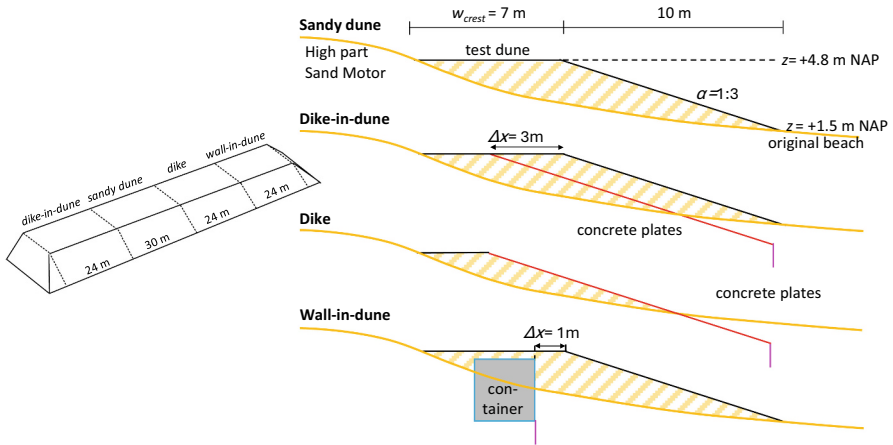
In a large field experiment, an artificial life-size hybrid dune was constructed just above the high water line, to systematically observe its response during storms (Fig. 1). Methodologically, this resembles the RealDune experiment (Van Wiechen et al., 2023), where an artificial life-size sandy dune was studied. For the new Hybrid Dune experiment, the test dune contains four cross sections (Fig. 2), of 24 to 30 m wide: 1) a classical sand dune section as baseline; 2) a dike with a hard revetment of concrete  $2 \times 2$  m tiles; 3) a hybrid dike-in-dune section, with the same hard revetment covered by sand and 4) a dune with a vertical sea wall in the dune, made from shipping containers. The experiment took place at the Sand Motor in the Netherlands. The setup was constructed in December 2024. Measurements started on 18 December 2024 and run during the winter of 2024/2025.



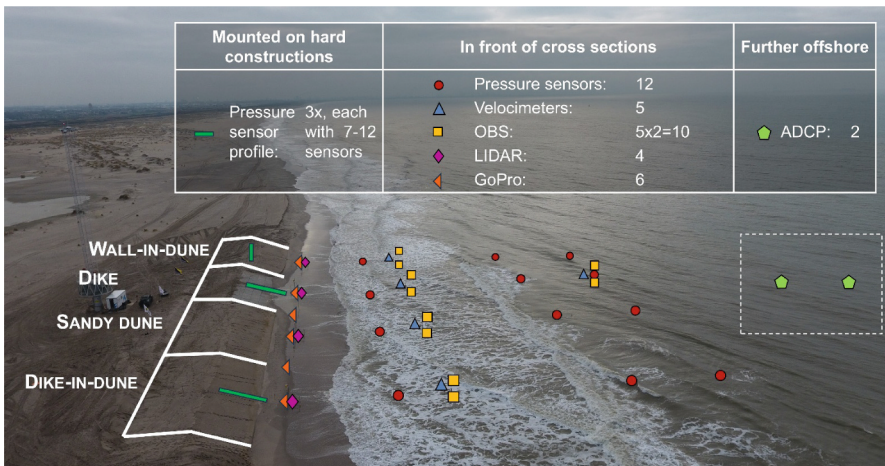
**Fig. 1.** The test setup just after construction, with the concrete tiles of the dike section visible and the hard elements of the dike-in-dune and wall-in-dune still hidden under the sand.

The measurements include water levels, wave action, current velocities, sediment concentration, hydrodynamic loading on the hard structure in terms of pressures and

morphological evolution of the dune and foreshore. Hereto an extensive array of sensors is employed (Fig. 3), including 2 offshore ADCP's; 5 ADV's with each 2 OBS sensors in front of the cross sections, 12 pressure transducers in the intertidal zone and 30 on the hard-soft interface, 4 multi-line lidar scanners and 6 GoPro's. In addition, topography is surveyed using a handheld GPS and lidar drone.



**Fig. 2.** The four cross sections of the experiment. The dune toe is located just above spring tide level.

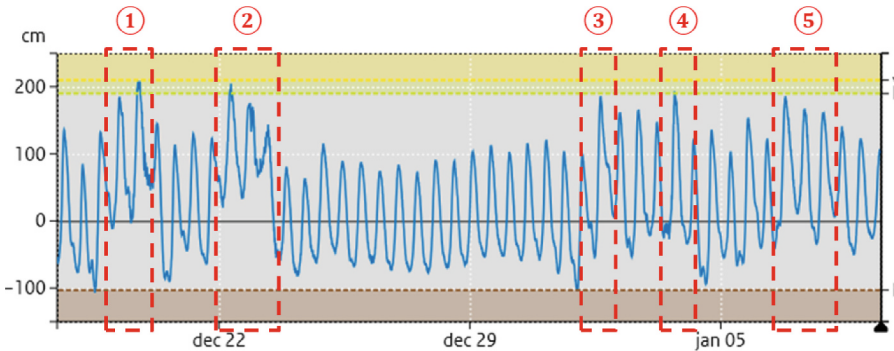


**Fig. 3.** Overview of the instrumentation used, projected onto an aerial photo of the experiment.

### 3 Results and Conclusions

The experiment has resulted in a unique dataset of concurrent high-resolution observations of hydrodynamics, sediment transport, morphological evolution of the dune and foreshore, wave runup and wave load on the structures. This will enable quantitative analysis of the morphological response to hydrodynamic drivers and hybrid dune configuration. Moreover, these observations can be used to include hybrid dunes in numerical dune erosion models. Early results show that strong erosion occurred, caused by several storms during the measurement period.

Five storms occurred during the experiment to date (Fig. 4), with peak water levels ranging between 1.84 m NAP (storm 3, Jan 1 2025) and + 2.08 m NAP (storm 1, Dec 19 2024). This caused strong erosion at the setup. At the dike-in-dune, the first storm already uncovered the first of the initially-covered revetment. The subsequent storms uncovered more of the revetment (Fig. 6), allowing the revetment to interact with the waves and sand transport, and giving us the opportunity to see how this affects the morphology in the surroundings. At the wall-in-dune section, the containers were still hidden under the sand after the first storm (Fig. 5), but they were uncovered in the second storm, with the dune cliff afterwards exactly in line with the front of the containers. During subsequent storms, erosion and dune retreat continued.



**Fig. 4.** Observed water levels in cm NAP during the experiments, based on a public measurement station at 8 km from the test site. Source: Rijkswaterstaat (2024).

Sand eroded from underneath the revetment, both from the edges of the dike- and dike-in-dune section and through gaps between tiles. This resulted in a gradual collapse of the revetments, starting at the edges of the dike section after the first storm (Fig. 5) and eventually resulting in the destruction of the dike- and dike-in-dune after the fourth storm. Given the early onset of revetment failure at the edges of the sections (a consequence of the loose concrete tiles used to facilitate deconstruction after the experiment), we concentrate here on the morphological development in the center of the cross sections.



**Fig. 5.** The setup on 20 Dec 2024, after the first storm. The tiles start to collapse at the edges of the dike section. The container (background) is still fronted by a meter of sand.



**Fig. 6.** The revetment of the dike-in-dune is partially uncovered after two storms. Erosion underneath the tiles causes the pates at the edges of the section to collapse.

Remarkably, morphological differences between the different cross sections appeared to be limited (Fig. 7). At the edges between the sandy dune and the concrete tiles, the beach was visibly lower, up to a couple of decimeters, leading locally to a faster retreat of the dune cliff. But no scour was visible in front of the hard revetments, nor in front of the vertical wall. The beach elevation in front of the setup, a couple of meters seaward of the position of the concrete tiles, seemed also very similar at the four cross sections. Wave runup and reflection differed by necessity between the cross sections due to the hard elements, but this had limited effect on the beach morphology. While further examination of the measurements is still needed to fully grasp the morphological differences and their drivers, it seems that the beach response in front of the



**Fig. 7.** The setup at 1 January 2025, the onset of high tide of storm 3. The cliff location and beach elevation are mostly uniform alongshore.

hybrid dune was primarily governed by the large-scale sediment supply, beach elevation and hydrodynamic conditions, rather than the hard-soft interactions at the hybrid dune.

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