# XBEACH SIMULATIONS OF A HYBRID COASTAL RISK-REDUCTION MEASURE: A GALVESTON SEAWALL TEST CASE

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The City of Galveston is protected from extreme storm impact by a 17-km concrete seawall facing the Gulf of Mexico. Recent studies have shown that the seawall may not be sufficient to protect against a 100-year design storm. Since raising the seawall disconnects the city from the beach and may be very costly, a hybrid approach is explored in which the existing hard structure is fronted and covered by a layer of sand. By means of numerical simulations, the hydro- and morphodynamic effects of adding a sand cover to the Galveston Seawall under extreme storm conditions are further investigated. It was found that by adding a sand cover over the seawall, maximum dissipation is spread over a larger cross-shore extent. This led to the reduction of the wave height at the face of the hybrid structure, as well as the generation of more wave-induced setup. Different hybrid design configurations were simulated, which varied in sand cover dimensions. Differences in wave attenuation, wave-induced setup and required sand cover volumes are discussed. It was found that a hybrid measure shows potential in reducing wave impact during extreme storm events, thereby reducing the required elevation of the Galveston Seawall.

*Keywords: coastal risk reduction, hybrid structure, Galveston Seawall, numerical modelling, XBeach, Building with Nature*

## INTRODUCTION

### Galveston Bay and hurricane prevention strategies

The Greater Houston Metropolitan Area (GHMA) is located on the Gulf of Mexico (GoM) coast of the United States and encompasses the city of Houston, Galveston Bay and its six surrounding counties, several ports, as well as the City of Galveston that is located on the barrier island of Galveston (Fig. 1). Galveston Bay is of great economic and ecological importance, but at significant risk from hurricane-induced surge, wave impact and flooding. In order to protect the bay and surrounding communities, proposals are being put forward to protect this area with a combination of measures in and around the bay (e.g. Merrell and Whalin, 2013; SSPEED Center, 2015). These proposals include the existing Galveston seawall (GSW), a 17-km, MSL + 4.2 m concrete structure facing the GoM, protecting the City of Galveston (NOAA, NGS, 2017; USACE, 1981).

Recent investigations have shown that the seawall may not be sufficient anymore to protect against the high water levels and the wave impact of a 100-year design storm. A possible solution is increasing the seawall's dimensions (Jonkman et al., 2015). This would require a large investment. Furthermore, increasing the elevation of the seawall is at odds with the open connection and character of the beach and City of Galveston, which has large communal value (Angelou Economics, 2008).

An alternative could be found in a hybrid approach, in which the existing hard structure is covered by a layer of sand resembling a dune (see Fig. 2). During extreme storm conditions, the dune will gradually be eroded, exposing the seawall. The redistribution of sediment during a storm from the dune face towards the shallow foreshore will lead to wave attenuation by the shallow foreshore as waves propagate into the nearshore and finally break against the exposed structure. However, the significance

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of this wave damping effect for the Galveston seawall during potential hurricane events is unclear. It is also unclear to what extent water levels are enhanced by wave-induced setup, when wave energy is dissipated more in the nearshore and balanced by a water level gradient.

In this numerical model study, we explore the effects in reduction of hydraulic loads by adding sand covers with various dimensions to the GSW taking into account potential adverse effects by the increase in wave setup.


**Figure 1. Location map showing Galveston Bay and the Upper Texas Coast, harboring Houston and its port and the city of Galveston, protected by the GSW.**

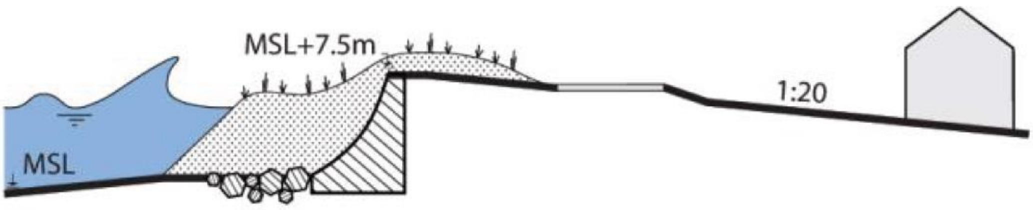


**Figure 2. Schematic overview of sand cover over the GSW (Jonkman et. al. 2015).**

## METHODOLOGY

### Hybrid designs

A total of 33 conceptual designs were simulated using XBeach. Each simulated design consisted of a unique sand cover configuration with variations in certain dimensions, such as beach height, beach length, dune width and dune slope. The dune slope is taken as the ratio between the vertical and horizontal dimension of the dune face (Fig. 3). One design requirement was to keep the elevation of the GSW as low as possible. In order to prevent overflow during the peak of the 100-year storm surge, the GSW had to be heightened to a minimal elevation of MSL + 6.5 m. The sand cover was added to the initial bathymetry including the GSW, which was defined as a non-erodible layer (Fig. 4). In addition, several designs were made to explore the effect of transforming the GSW into a sloped impermeable seadike in combination with a sand cover. An overview of a selected subset of design dimensions is shown in Table 1. Further simulated design configurations are not shown here.

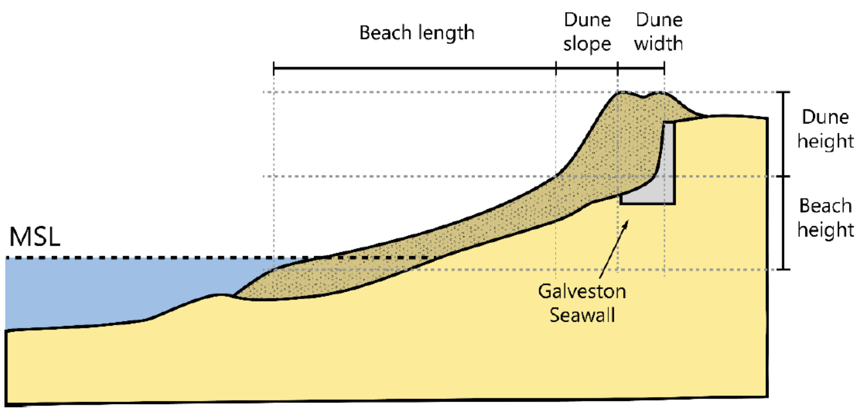


**Figure 3. Schematic cross-section of the hybrid setup under consideration. Design parameters that were varied as part of this study are displayed.**

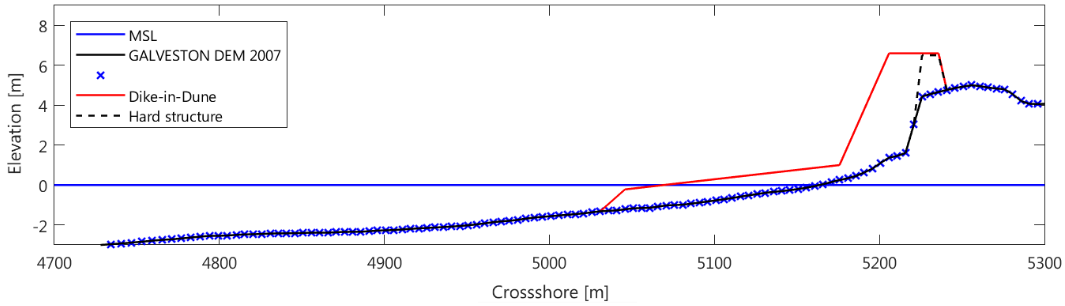


**Figure 4. Cross-section of hybrid setup for simulation with run ID 2.10 (see Table 1). In this case GSW is increased to MSL + 6.5 m.**

**Table 1. Design parameters of subset of simulated configurations. The subset is grouped based on the geometry parameter that is varied within the design**

| Geometry parameter | Run ID | Dune height [m] | Dune width [m] | Dune slope [m] | Beach width [m] | Beach height [m + MSL] |
|---|---|---|---|---|---|---|
| Dune width | 2.20 | 7.1 | 10 | 1:3.5 | 110 | 1.0 |
| | 2.19 | 7.6 | 20 | 1:3.5 | 110 | 1.0 |
| | 2.18 | 7.1 | 40 | 1:3.5 | 110 | 1.0 |
| | 2.21 | 7.6 | 60 | 1:3.5 | 130 | 1.0 |
| | 2.10 | 6.6 | 20 | 1:5.5 | 130 | 1.0 |
| Dune slope | 2.13 | 6.6 | 10 | 1:3.5 | 110 | 1.0 |
| | 2.11 | 6.6 | 10 | 1:5.5 | 110 | 1.0 |
| | 2.16 | 6.6 | 10 | 1:8.0 | 110 | 1.0 |
| Beach height | 2.24 | 6.6 | 10 | 1:3.5 | 95 | 2.5 |
| | 2.25 | 6.6 | 10 | 1:5.5 | 130 | 3.0 |
| | 2.28 | 6.6 | 5 | 1:8.0 | 130 | 3.5 |

## Numerical model

In order to simulate the behavior of various sand cover dimensions over the GSW, during an extreme storm event, we use the numerical model XBeach (Roelvink et al., 2009). This 2DH process-based model was developed to simulate hydrodynamic storm conditions and their impacts on coastal morphology. It does this by solving the shallow water wave equations, including a time-varying wave forcing term and depth-averaged undertow.

The wave energy is calculated by solving a short wave averaged 2DH formulation of varying wave conditions on a wave group scale allowing for phase-resolving solutions of infra-gravity waves. The model is able to formulate time-varying wave action, including refraction, shoaling, current refraction and wave breaking. The model also includes a roller formulation, which represents the momentum stored in surface rollers, wave-current interactions and a wave dissipation model.

The complex surf and swash zone sediment transport is calculated through the Soulsby-Van Rijn relations and is subsequently used to calculate the suspended sediment transport by solving the depth-averaged advection-diffusion equation. Bed level updating is accomplished by solving the sediment transport mass balance. Furthermore, XBeach describes the avalanching of dune faces during a storm via exceedance of the critical wet and dry slope of the dune face. XBeach allows for the inclusion of a non-erodible layer, which determines how much material is available for transport at a cell node.

#### Model setup

The model domain covers a 6 km cross-shore and 5 km alongshore extent. A rectangular computational grid was defined, with a varying grid resolution of $\Delta x$ = 5 to 15 m and $\Delta y$ = 10 to 20 m. The model's bathymetry was retrieved from a digital elevation model (DEM) of Galveston Island, which is compiled of multiple surveys dating from 1980 to 2002 with a 1/3-arcsecond resolution. Topography in the nearshore and behind the seawall was simplified and does not vary in the alongshore direction. The GSW was included as a non-erodible layer and is still exposed in the initial setup (Fig. 4). Bed roughness was incorporated via a constant Chezy coefficient of 55 $m^{1/2}/s$. The sediment grain size was $D_{50}$ = 150 µm and $D_{90}$ = 187 µm (Harter, 2015; Texas General Land Office, 2016; USACE, 2014). Further parameters were kept at default settings as described by XBeach or other studies with similar conditions (McCall et al., 2010; Roelvink et al., 2009).

The model was forced with an incoming surge and wave signal defined at the offshore boundary. The two lateral boundaries of the model domain were defined as Neumann boundaries, to allow for any alongshore-generated currents or waves to correctly propagate out of the domain. No boundary conditions were defined at the landward boundary (Fig. 4).

The model setup was used to simulate various hybrid designs during a synthetic 100-year design storm. This storm consists of a time-varying incoming surge level and waves that were derived based on earlier studies on the Upper Texas Coast. Storm duration is based on Hurricane Ike and consists of 90 hours. The surge level includes a peak surge of 4.71 m and a forerunner surge of 3 m arriving 6 hours prior to hurricane landfall (Lendering et al., 2014), as indicated in Fig. 5. The effect of relative sea level rise, e.g. subsidence and absolute sea level rise is accounted for by adding 0.5 m of additional elevation (Paine, 1993; NOAA, 2016b). Peak wave height and wave period values were adopted from extreme value analyses in previous studies (Almarshed, 2015; Jin et al., 2010; van Berchum et al., 2016) and are incorporated into Fig. 6. The characteristic temporally varying storm profile is based on the measured water level data during Hurricane Ike (Kennedy et al., 2011b, 2011a).

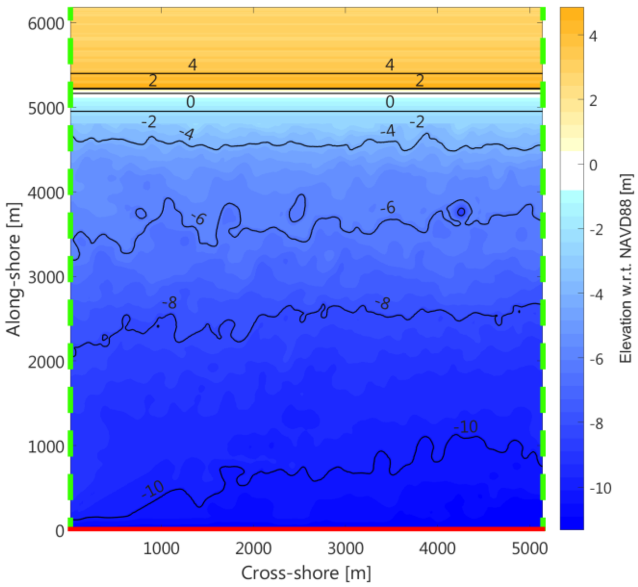


**Figure 4. Model domain with initial bathymetry, composed of measured bathymetry offshore and simplified profile behind the seawall. In the initial setup, no sand cover is added and the seawall is exposed. Incoming surge and waves are described at the offshore boundary (red). The lateral boundaries were defined as Neumann boundaries (green).**

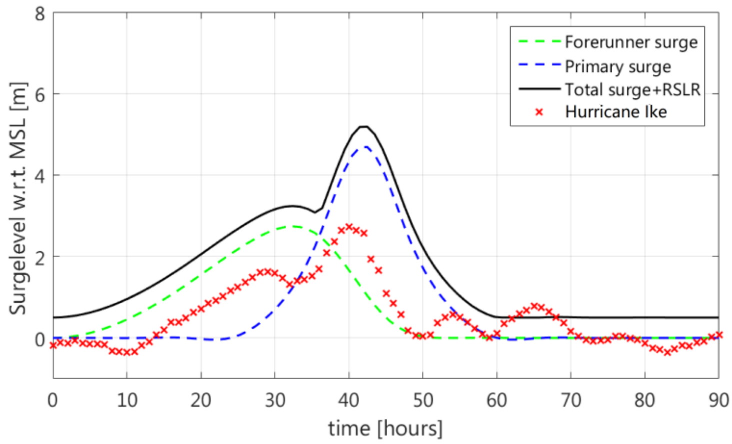


**Figure 5. Time series of storm surge level for a 100-year event including forerunner surge (green) and primary surge (blue) (Lendering et al., 2014) and final combined surge level accounting for RSLR (black). Reference is made to measured surge levels during Hurricane Ike at offshore buoy S42035 (NOAA, 2016a).**

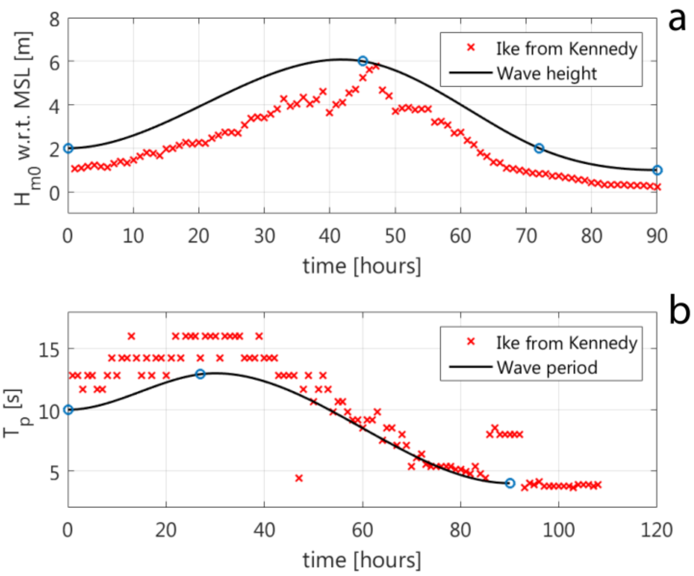


**Figure 6. Time series of design significant wave height (a) and peak wave period (b) used for the hybrid simulations (black). Reference is made to the measured wave height and period during Hurricane Ike by rapidly deployed buoys in around 10 m water depth along the Upper Texas Coast (Kennedy et al., 2011a).**

## RESULTS

### Model validation

The model performance on predicting surge level and bed level updating during an extreme storm event is validated by hindcasting Hurricane Ike at east- and west-end sections of the Galveston coastline, where the former is sheltered by the GSW and fronted by small dunes. The latter is at the west end of the GSW and only small dune formations were present. Surge levels were visually validated by comparing predicted and measured time series (Kennedy et al., 2011a, 2011b; NOAA, 2016c; USGS, 2008). Morphological development was validated both visually and statistically through pre- and post-storm LiDAR data (NOAA, 2006, 2009).

Validation results show satisfactory model performance regarding the water level. An important indication is the ability of the model to predict magnitude and timing of the maximum surge for both the nearshore location at Pleasure Pier in front of the GSW (Fig. 7a) and the onshore location at the west-end of the GSW, where overflow occurred (Fig. 7b). Before Hurricane Ike, small dune formations were present at the west end of the GSW. Results suggest that the model slightly overpredicts erosion volumes of the dune face and over the island as indicated in the profile evolution results shown in Fig. 8, where three different island cross-sections at the west end of the GSW are shown. The slight overprediction in erosion volumes might be attributed to the effect of vegetation and non-erodible surfaces present at the coastline, but is most likely related to the simplified process-based approach used in the model. Overall the model shows satisfactory performance to be used in the simulation of hybrid designs.

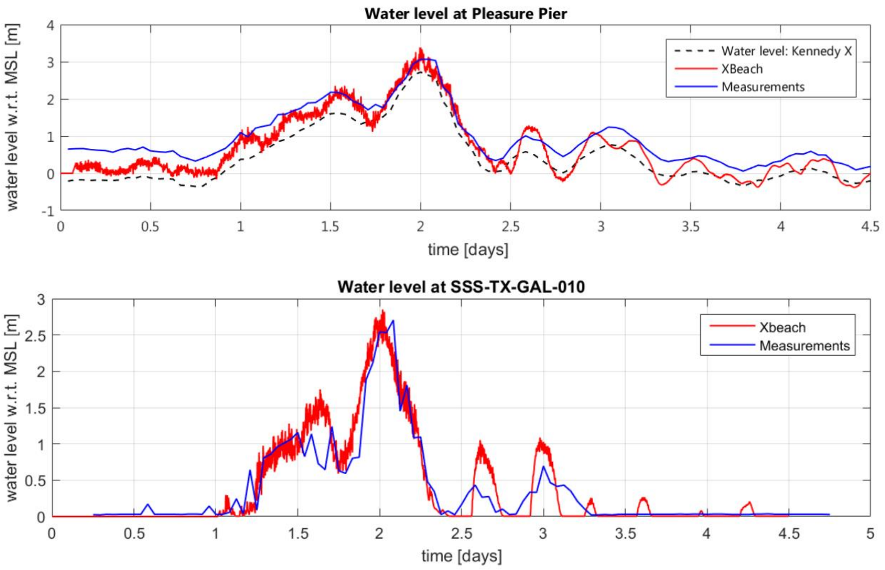


**Figure 7. Storm surge validation between predicted (red) and measured (blue) water levels for the Galveston Pleasure Pier tidal gauge (SID: 8771510; 29°17.1´N; 94°47.3'W (NOAA, 2016c)) in front of the GSW (top panel) and at a temporary onland gauge (SID: SSS-TX-GAL-010; 29°14.1'N 94°52.4'W (USGS, 2008)) at the west end of the GSW, where only small dunes are present (bottom panel).**

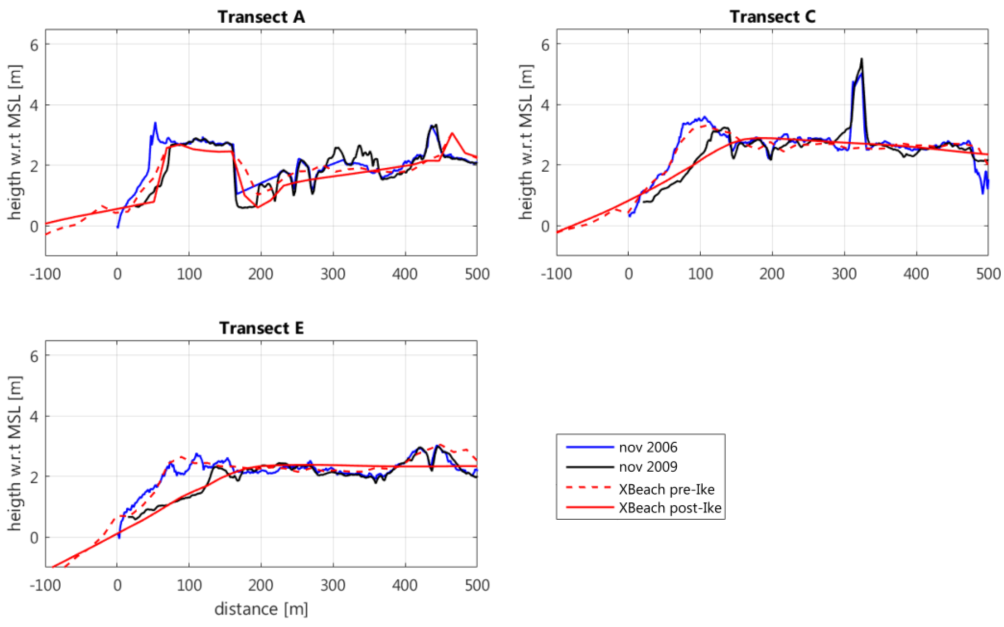


**Figure 8. Predicted and measured cross-shore profiles before and after Hurricane Ike impact at the west end of the GSW on Galveston Island. Transect A is located just west of the west end of the GSW and features several non-erodible structures, such as a parking lot and elevated roads. Transects C and E are located westward of transect A and feature only small dune formations. The large elevation in the middle of Transect C represents a man-made structure and was not included in the model.**

### Wave energy dissipation by this hybrid design

First, a reference case was tested, in which the current seawall is extended and no additional sediment cover was added. Fig. 9 shows a cross-section of the model setup and a timestack representation of the wave energy dissipation. During the peak of the storm (~ 45 hrs.), most of the dissipation takes place at the seawall with very high local dissipation rates (1241 $W/m^2$ at 5220.8 m in the cross-shore extent).

Next, a variant is shown with a sand cover on top of the seawall (Run ID 2.10). The maximum dissipation rates are lower and the location of maximum wave energy dissipation has shifted offshore from the seawall (503 $W/m^2$ at 5180.8 m). This shift in maximum dissipation and location is caused by the added sediment spreading out in the offshore direction from the hybrid structure, leading to smaller water depths in the nearshore and a modified surf zone. During the storm, the dune face gradually retreats and eroded sediment is deposited in the nearshore. This leads to even more reduction of the nearshore water depth and subsequently higher dissipation rates.

### Wave attenuation by different sand cover dimensions

Previous results showed the spreading of wave dissipation over a larger area in the cross-shore extent of the model domain and reduction of the maximum dissipation rate, as a result of adding a sand cover over the GSW. As more dissipation occurs inside the nearshore zone, resulting wave height is subsequently reduced as waves propagate towards the shore. Multiple sand cover designs were simulated to explore the effect of increasing sand cover volume, $V_{cover}$, (e.g. by changing various sand cover geometry parameters, such as dune width, dune slope, beach height and beach length) on this wave attenuation. Wave height at the face of the hybrid structure, $H_{b,max}$, was determined by retrieving the wave height during the peak of the storm at either the dune face or the toe of the seawall once exposed (Fig. 9).

Increasing sand cover volume, $V_{cover}$, by means of varying the profile geometry generally leads to decreased $H_{b,max}$ (Fig. 10). The reference case (Run ID 1.1) consists of a seawall with increased elevation but without a sand cover and shows the largest wave height at the face of the structure during the peak of the storm ($H_{b,max}$ = 2.96 m). Adding a sand cover, for instance, by increasing the dune width, shows a decrease in wave height ($H_{b,max}$ = 2.38 ~ 1.84 m or 80 ~ 62% to the reference case). However, this effect weakens as a larger sand cover volume leads to less exposure of the seawall during the storm. In this case, all dissipation occurs over the dune face and does not increase as a result of increased sand cover volumes. Run 2.21 even shows an increase in wave height at the face of the hybrid system, which is due to the increase of multiple design dimensions (Table 1). Other design parameters, such as dune slope or beach height show similar reduction of wave heights at the face of the hybrid structure (2.34 ~ 1.86 m; 79 ~ 62% and 2.34 ~ 1.71 m; 80 ~ 57%, respectively). However, lower sand cover volumes are required to obtain comparable reductions in wave height relative to the options based on increased dune width.

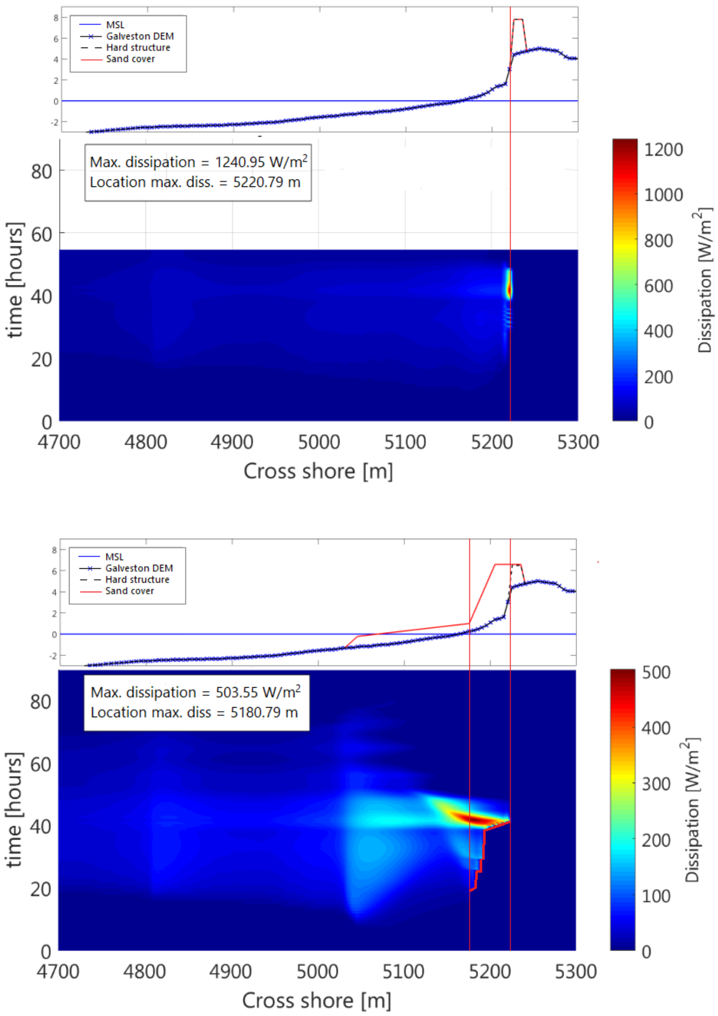


**Figure 9. Characteristic cross-section and cross-shore wave dissipation timestack for the reference case (upper panel) and hybrid design with Run ID 2.10 (lower panel). The reference case was stopped at 55 hours as maximum dissipation had passed. Indicated by the red line is the location of either the dune face or the toe of the seawall once exposed for retrieving the maximum wave height at the face of the hybrid structure.**

### Wave height vs. wave-induced setup

As wave energy is being dissipated, a wave force is generated directed towards the shore. This wave-driven hydrodynamic force is subsequently balanced by a (positive) water level gradient, or wave-induced setup. Fig. 11 shows the predicted maximum wave height at the face of the hybrid structure, $H_{b,max}$, versus the maximum wave-induced setup, $\eta$, where the setup is defined as the difference between the water level measured at the face of the hybrid structure and the offshore water level ($\eta = h_b - h_0$). These results show an inversely proportional relationship between the maximum wave height and setup at the face of the hybrid structure. In case of no sand cover (Run ID 1.1), relatively large wave heights are still present at the toe of the seawall ($H_{b,max}$ = 2.96 m) and a relatively small setup results ($\eta$ = 0.92 m). As sand cover volumes increase through increasing certain design dimensions (e.g. dune width, dune slope, or beach height), the wave height near the face of the hybrid structure decreases and setup gradually increases as shown in Fig. 11.

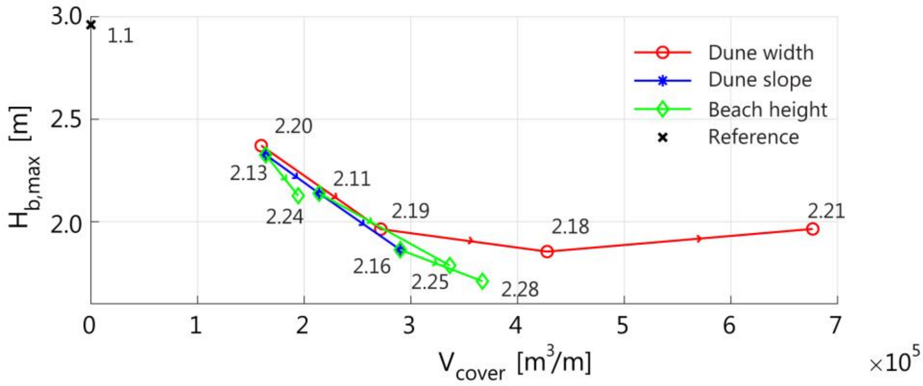


**Figure 10. Wave height at the face of the hybrid structure versus the volume of sand material covering the structure. An overview of the design parameters for the displayed cases can be found in Table 1.**

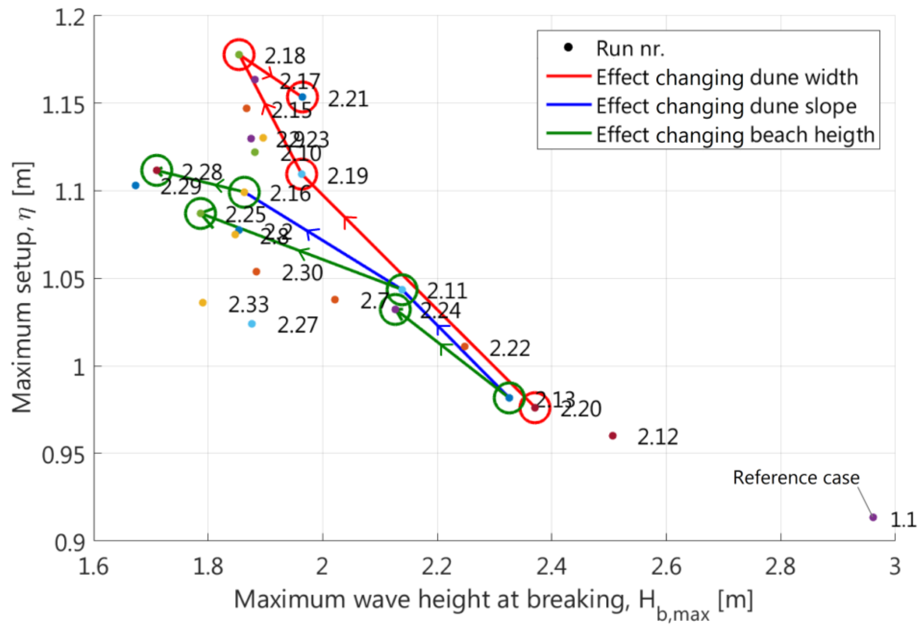


**Figure 11. Wave-induced setup, $\eta$ (= $h_b$ - $h_0$) versus the maximum wave height $H_{b,max}$ at the face of the hybrid structure (see Fig. 9). Indicated are the values of all usable simulations (e.g. no overflow), where some sort of sand cover is added to the initial model setup. In case of no sand cover (Run ID 1.1), wave height remains relatively high ($H_{b,max}$ = 2.96 m) and little setup is generated ($\eta$ = 0.92 m). By adding a sand cover over the seawall, higher wave dissipation leads to lower wave heights near the face of the hybrid structure and a higher setup. Also indicated is the effect of increasing the sand cover volume through increasing either dune width (red), dune slope (blue), or beach height (green).**

## DISCUSSION

The results of the simulations show an inversely proportional relationship between the maximum wave height and setup near the face of the hybrid structure (Fig. 11). In general, larger sand cover volumes over the GSW lead to smaller water depths inside the nearshore zone and a modified surfzone as the dune face is gradually eroded during a storm event. Subsequently, wave dissipation is shifted towards the nearshore zone, occurring over a longer cross-sectional extent. This leads to a reduction in wave height at the face of the hybrid structure, as well as the generation of a relatively higher wave force and subsequently balancing wave-induced setup.

In a situation with no additional sand cover, most of the breaking and dissipation is concentrated at the seawall itself and energy is partly reflected (Fig 11, Run ID 1.1). As a result, the wave height at the toe of the seawall is relatively high ($H_{b,max}$ = 2.96 m) and only minor setup is generated. The effect of adding a sand cover to the seawall, can lead to a 40% (or 1.2 m) decrease in wave height (Run ID 2.18) at the face of the hybrid structure and an increase of up to 25% (or 0.18 m) in setup (Run ID 2.29) in comparison to no sand cover.

Furthermore, the influence of the seawall slope was investigated. Several simulations were done with a sloped non-erodible seawall in combination with a sand cover (Fig 11, Run ID 2.27; 2.33). The results show a lower wave height at the face of the hybrid structure without increasing the wave-induced setup. In comparison to a non-sloped seawall, when the sloped seawall becomes exposed, the reduced wave height finally dissipates on the fixed slope. This, in combination with the added sand cover, more effectively reduces the wave height at the face of the hybrid structure. Due to the relatively narrow area where this dissipation takes place, the effective surf zone is small and wave-induced setup remains relatively small.

## CONCLUSIONS AND RECOMMENDATIONS

This numerical model study gives an insight in the reduction of wave height by a sand cover over a seawall and the corresponding increase in wave-induced setup. The usage of XBeach for these hybrid structure designs showed reliable results with default model values. In order to rehabilitate the Galveston Seawall to provide sufficient protection, a sand cover can be used beneficially. Overall, larger volumes of sand cover led to increased wave energy dissipation in the approach to the seawall and lower wave heights at the structure. This means that the maximum elevation of the structure can be designed lower in comparison with traditional seawall revalidation proposals. However, due to the gradual wave energy dissipation, increased wave-induced setup is generated, suggesting a higher mean water level at the structure that has to be accounted for in the final elevation.

A more in-depth understanding could be obtained by simulating different design storm cases, studying longer along-shore sections and transition regions between different coastal risk-mitigation structures and by studying different sand and structure options and combinations. In addition, the practical feasibility of applying a hybrid solution has to be researched in more depth. The erosion of dune material during a storm event could result in this type of hybrid coastal system to require immediate post-storm maintenance of the sand cover.

## ACKNOWLEDGMENTS

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