OPTIMIZATION OF THE CLOSURE OF A BREACHED BARRIER ISLAND IN THE GULF OF MEXICO

Marius Sokolewicz[1], Dirk-Jan Walstra[2], Johan Henrotte[1] , Elizabeth Godsey[3]

A chain of barrier islands in the Gulf of Mexico reduces storm and hurricane impacts along the Mississippi coast. Ship Island, one of the largest islands of this chain, was breached by hurricanes Camille and Katrina creating a 5.5 kilometer wide gap. US Army Corps of Engineers plans to restore the island nourishing 15 million cubic meters of sand. Extensive modeling studies were carried out to support the environmental impact assessment and to optimize design. The main objective of these studies was to determine the impact of the restored island on the environment. The possible increase of sedimentation rates in the adjacent navigation channel connecting a major port to the Gulf of Mexico was of particular interest. The Delft3D models, calibrated on measurements of waves, tidal levels and currents, were used to estimate the annual sediment transport rates. These models were subsequently applied to optimize the design of the closure of Camille Cut. The optimum construction sequence was established. Sediment losses from the fill, and the impact of turbidity plumes on the nearby sea grass fields were determined.

Keywords: optimization closure strategy, sediment loss, turbidity plume, barrier island, Mississippi Coast, MsCIP, Delft3D, UNIBEST

INTRODUCTION

Background

A chain of barrier islands in the Gulf of Mexico reduces storm and hurricane impacts along the Mississippi coast. The islands are also an important ecological reserve, rich in wildlife and natural features. The islands are subject to natural erosion due to tides, waves, and tropical storms and hurricanes. Ship Island, one of the largest islands of this chain, was breached by hurricane Camille in 1969. In 2005 hurricane Katrina widened Camille Cut to 5.5 kilometers, caused severe erosion of the beaches and destroyed most of the vegetation on the island. As part of the Mississippi Coastal Improvements Program (USACE, 2012a; USACE 2012b), the US Army Corps of Engineers intends to restore sediment to the barrier island system at Ship Island to help maintain and sustain the barrier island and Mississippi Sound ecosystems by nourishing approximately 15 million cubic meters of sand to reconnect East and West Ship Island. Extensive modeling studies were carried out to support the environmental impact assessment and to optimize design. The main objective of these studies was to determine the impact of the restored island on the environment, in particular the possible increase of sedimentation rates in the adjacent navigation channel connecting a major port to the Gulf of Mexico. To that end, a cascade of numerical models (see Fig. 1) was constructed, which at the largest scale considered the entire Gulf and at the smallest scale covered East and West Ship Island and adjacent inlets. With Delft3D models, calibrated against measurements of waves, tidal levels and currents, annual sediment transports were established (Walstra et al., 2012a).

Study objective

The focus of the study presented in this paper was the evaluation and optimization of the dredging works to close Camille Cut. Several issues related to execution of the hydraulic fill were identified that could be critical to successful completion of the project:

1. *Optimum closure strategy*: The initial plan was to close the breach in Ship Island from East to West, following the natural sediment drift. However, this meant that the deepest part of the breach would be closed last, with a risk of strong currents potentially resulting in large sediment losses from the hydraulic fill.
2. *Sediment losses vs production capacity*: To close the breach, production capacity of the hopper dredge pumping sediment to the closure gap must be significantly larger than the loss of sediment to deep water by currents and waves; otherwise the project could become extremely costly, and lead to a significant risk of failure.

[1] Royal HaskoningDHV, Deltas, Rivers & Coasts, P.O. Box 1132, 3800 BC Amersfoort , The Netherlands
[2] Deltares, Hydraulic Engineering, P.O. Box 177, 2600 MH, Delft, The Netherlands
[3] U.S. Army Corps of Engineers, Mobile District, P.O. Box 2288, Mobile, AL 36628-0001, USA

3. *Stability of the fill*: The initial fill, to be constructed in the first year of the project, will be relatively narrow, and will be extended to its full width of more than 500 m only in the next season. During the first storm season the fill will be vulnerable to the impact of waves which could lead to breaching or unacceptably large sediment losses to deep water.
4. *Impact of turbidity plumes*: Large areas of sea grasses are located in close vicinity of the project. Plumes of suspended sediment caused by placing large volumes of dredged material could potentially adversely affect the sea grass. Exceeding the turbidity limits set by authorities could cause costly project delays and work stoppage.

The objective of the study was to analyze the risk associated with the above issues, and to propose optimization measures where necessary.

GENERAL APPROACH

The detailed numerical models, developed in an earlier stage of the project to assess the morphological impact of the restoration on the environment (Walstra et al., 2012a), were used to select the optimum closure strategy, to investigate the risk of breaching of the initial fill, and to estimate the impact of the turbidity plumes on the sensitive sea grass areas.

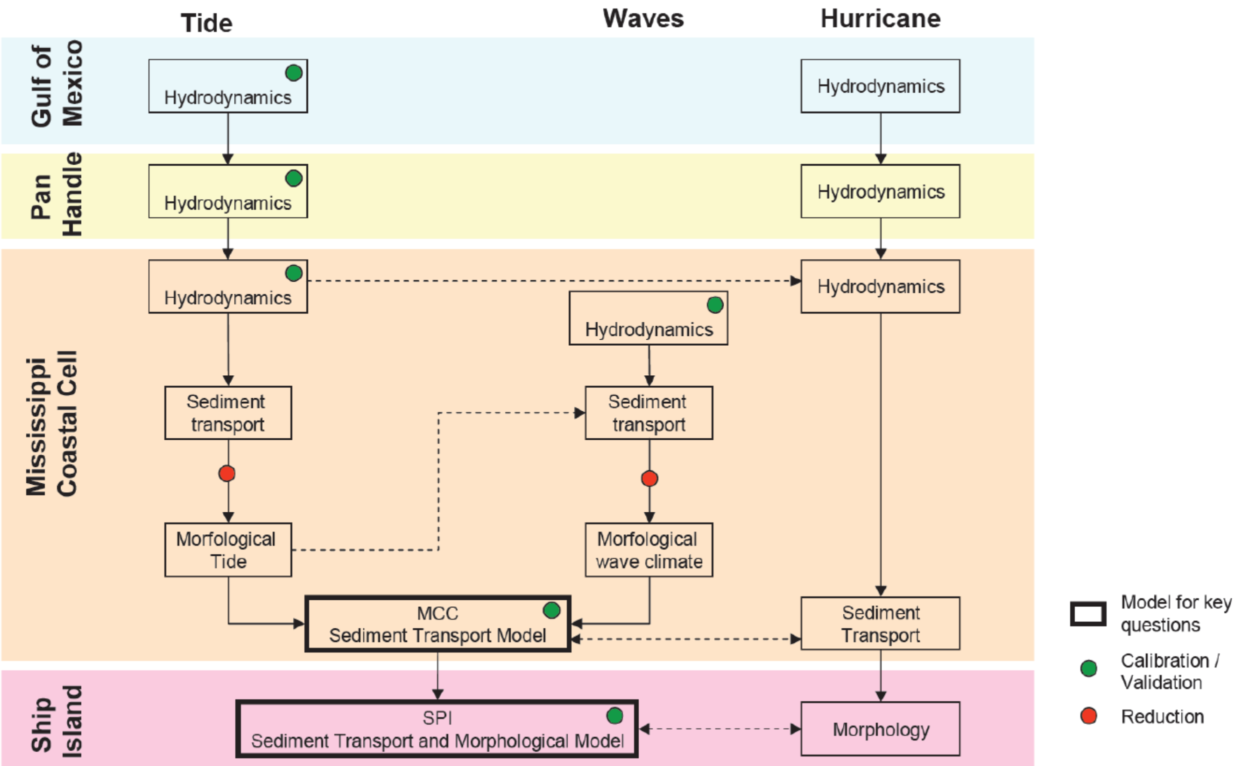


Figure 1. A cascade of models to determine the environmental impact of the restoration

The assessment was based on simulations with process-based numerical models (Delft3D and UNIBEST) for a set of typical climatic conditions and parameters representing the process of construction. Main parameters in this assessment were the characteristics of the fill material, the production cycle and the fill production capacity. To evaluate the designed cross-section stability and the risk of breaching, the advanced process-based cross-shore model UNIBEST-TC was used (Ruessink et al., 2007; Walstra et al., 2012b). The estimation of sand losses and turbidity levels during construction were carried out using the Delft3D model (Lesser et al., 2004; Van Rijn et al., 2007).

OPTIMUM CLOSURE STRATEGY

Selection of closure strategies

The hydraulic fill to close the breach in Ship Island can be constructed in many different ways. In the study, three basic closure strategies were evaluated to determine the optimum strategy (see Fig. 2):

1. Closing from East to West (base strategy);
2. Closing from West to East
3. Closing from both sides

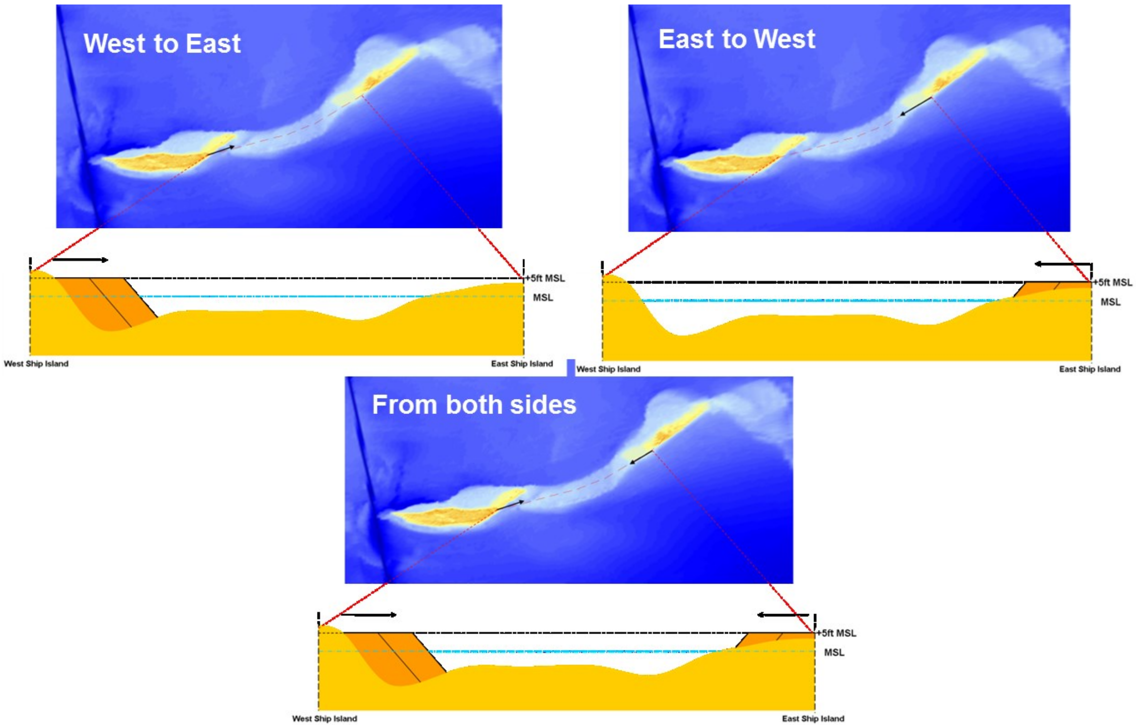


Figure 2. Possible closure strategies

2D model simulations were used to investigate the maximum tidal flow velocities that would develop in the closure gap at different stages of construction for the three closure strategies, and to investigate the sediment loss in the closure gap in the most critical stages of filling.

Hydrodynamic conditions in the closure gap

Hydrodynamic simulations using a detailed hydrodynamic (Delft3D) model, covering the full neap-spring tidal cycle, were executed to determine the change of the current velocities in the closure gap at various stages of the work. Different closure scenarios were considered, with hydraulic fill advancing from east to west, from west to east and from both sides. These simulations showed that in all considered strategies, the most critical part of filling was around 70-90% of the closure (see Fig. 3). However, the flow velocities were found to remain within acceptable limits for all strategies. Upon this finding, the strategy "West to East" was dropped from further investigations since it did not offer any significant advantages in flow velocity reduction and would result in full closure occurring against the direction of dominate sediment transport.

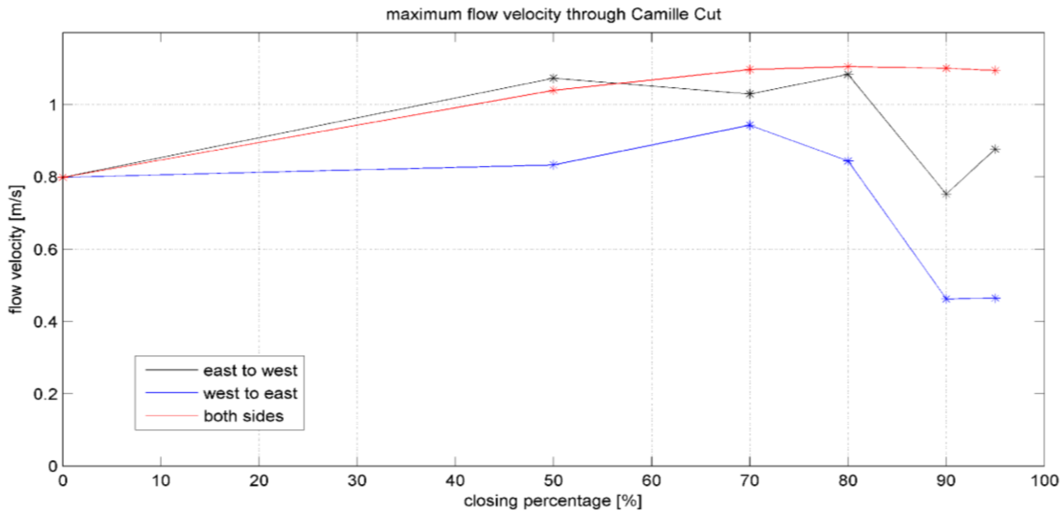


Figure 3. Maximum flow velocity in the closure gap for different stages of work and different closure strategies.

Sediment losses in the closure gap

The processes of erosion and sedimentation occurring at critical stages (70-90%) in the closure gap were modelled in the detailed sediment transport model (Delft3D). The rate of erosion from the hydraulic fill occurring during one tidal cycle was compared with the estimated production rate of the hopper dredger (18,000 m³/day).

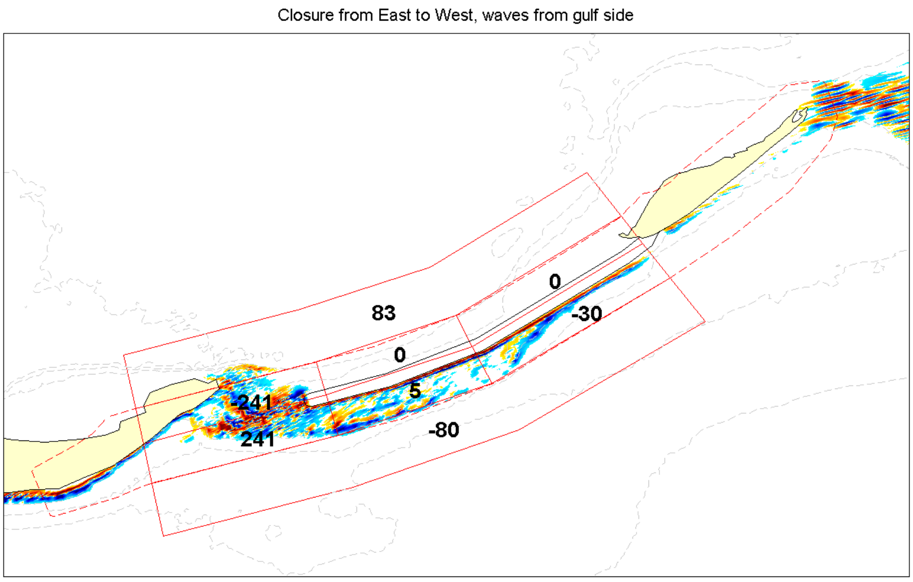
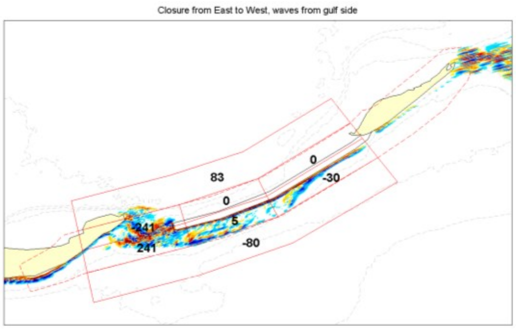


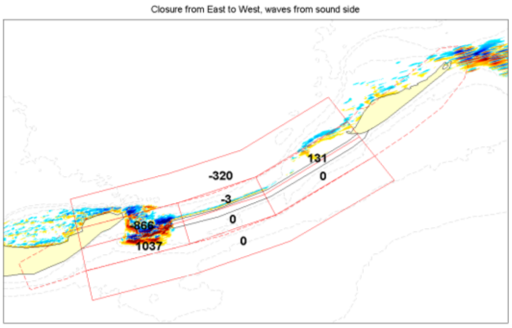
Figure 4. Example of sediment balance in the control boxes around the hydraulic fill (70% closure, tide + waves, East to West strategy); Colors indicate sedimentation and erosion (see Figure 6 for color scale).

To determine the sediment loss, initial bed changes were analyzed. The activity of the dredge pumping a slurry to the gap was modeled as a source of sediment. The area within the final fill template was divided into several control boxes, and the sediment mass balance in these boxes was determined for different hydrodynamic conditions (see Fig. 4). An assumption used in the study was that sediment that would be eroded by currents and waves from the initial template would not be considered lost to deep water as long as it remained within the final template. Therefore, some erosion from the initial template was allowed.

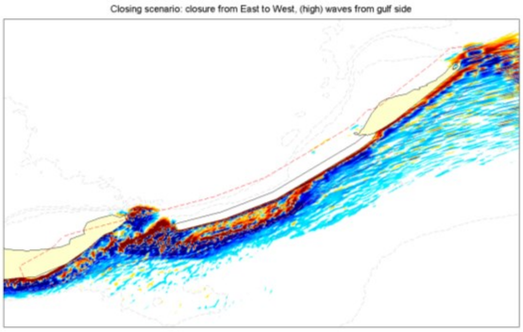
An important finding was that not only losses from the sediment pumped into the closure, but also the erosion of the native sediment in the breach itself, occurring as a result of flow constriction is an important factor, requiring additional sediment to be pumped into the closure gap.



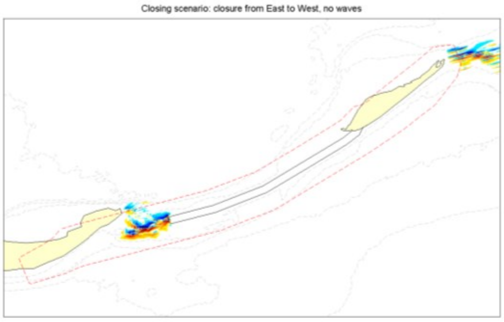
a) moderate wave condition from Gulf side



b) moderate wave condition from Sound side



c) storm condition from Gulf side



d) no waves, only tide

Figure 5. Sensitivity of sediment losses in the closure gap for different hydrodynamic conditions; Colors indicate sedimentation and erosion (see Figure 6 for color scale).

For the base scenario: moderate waves from the Gulf side, combined with spring tide flow, and the closure strategy East to West, sediment losses to deep water were found to be insignificant. In order to eventually close the gap, the production rates of a hopper dredge should exceed the erosion rates near the construction head. Every 8 hours an estimated total amount of 6,000 m^3 will be placed at the head of the fill. This will be significantly more than approximately 100 m^3 estimated which will be eroded away during flood from the area in vicinity of the fill's head.

A sensitivity analysis was carried out to assess the impact of variation in the hydrodynamic forcings (see Fig. 5). This analysis showed that for the East to West strategy, even during storm conditions in the Gulf, the sediment losses to deep water will be very limited. Waves from the Mississippi Sound side (north of the island) will have very limited impact, and tidal flows without wave action results in minor erosion.

The sediment losses appear to be 10 times larger for the "closure from both sides" strategy (see Fig. 6). Although local bed level changes were predicted to be mostly within the footprint of the final template, about 5% of the pumped sediments was lost beyond its distal limits.

This assessment confirmed that the base closure strategy East to West as initially selected by USACE represents the optimum closure strategy.

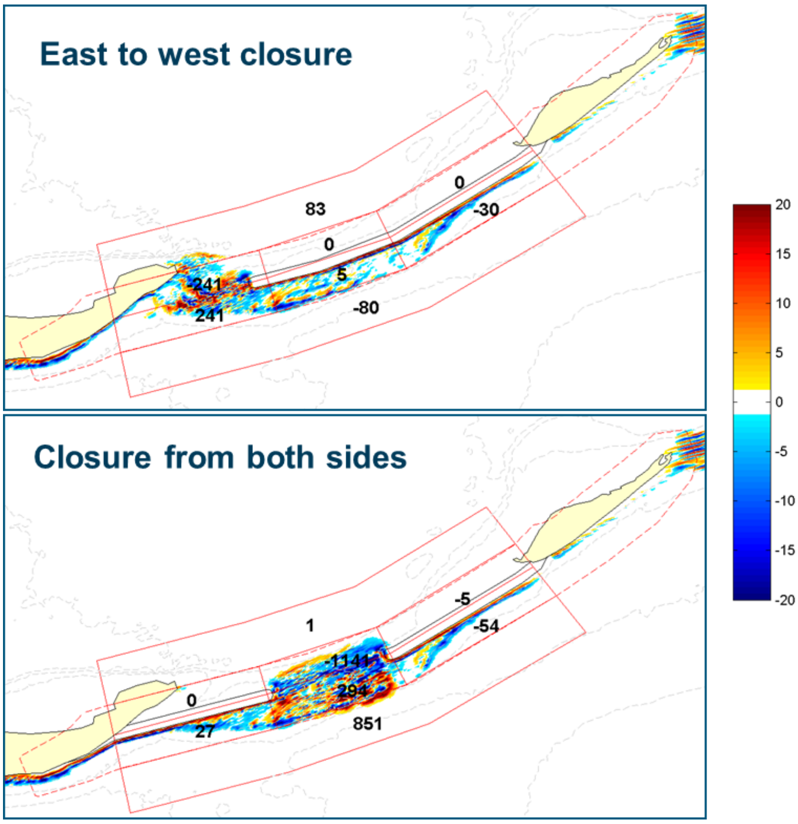


Figure 6. Comparison of sediment losses between two closure strategies, for the base scenario. ; Colors indicate sedimentation and erosion (yellow-red colors indicate accretion, blue colors indicate erosion).

STABILITY OF THE HYDRAULIC FILL

Approach

The estimated construction period of the initial hydraulic fill is approximately 1 year. During this period, the cross-shore profile will evolve due to action of wind, waves and currents. To determine the extent the initial cross-shore profile would evolve to during this construction period, morphological cross-shore computations were executed by using the UNIBEST-TC model.

The cross-shore profile development simulated by UNIBEST-TC depends on the sequence of wave forcings imposed in the model. As only the annual wave climate was available for this study, to determine the bandwidth of possible profile development, four different time series with different wave sequences were considered:

- wave conditions sorted randomly (wave sequence 1 and wave sequence 2);
- wave conditions sorted from highest to lowest significant wave heights (wave sequence 3) and
- wave conditions sorted from lowest to highest significant wave heights (wave sequence 4).

Furthermore, the sensitivity of the results to the selected sediment grain size (base case: 0.300 mm, finer sediment: 0.210 mm) was analyzed.

Profile evolution

In order to study the development of the erosion front the cumulative loss of volume of the crest in time was investigated in detail for wave sequence 1, this is shown in Fig. 7; upper graph. At first, the erosion front increases, after just 50 days the total loss of volume in the crest zone is approximately 30 cubic yards per foot. After 100 days the profile reaches an equilibrium decreasing the erosion rate of the crest to nearly zero; the total loss of volume in the crest zone after 100 days is approximately 35 cubic yards per foot. From this point on the total loss of volume remains almost constant. After 150 days there is a short recovery period present. During the final stage the shape of the crest will still be reworked by waves, only there is no significant loss of sand out of the crest zone, indicating that a dynamic equilibrium has been reached. The total loss of sand in the crest zone at this stage varies between approximately 30 and 35 cubic yards per foot.

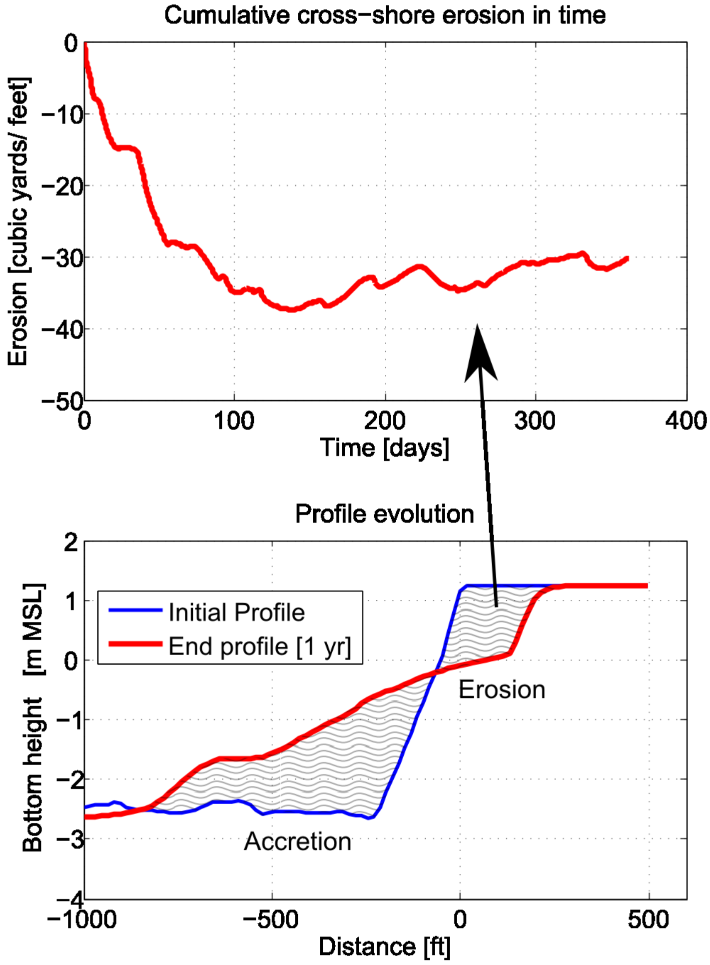


Figure 7. Upper graph: Cumulative volume change in time; Erosion at the crest zone. Lower graph: Profile evolution (Gulf side) as result of wave sequence 1

Fig. 8 shows the evolution profiles at the Gulf side, for the different sensitivity runs. Variation in slope and total eroded volume can be observed. The beach slope (above 0m +MSL) for all sensitivity runs is approximately the same, a slope of 1:100. However, the crest erosion width differs from 120 feet to 220 feet, and the resulting slope of the underwater profile varies strongly for the different wave sequences, from a 1:100 slope for sequence 1 and sequence 2 (random wave sequence) to 1:50 for sequence 3 (descending wave sequence). This provides a bandwidth of the expected profile changes.

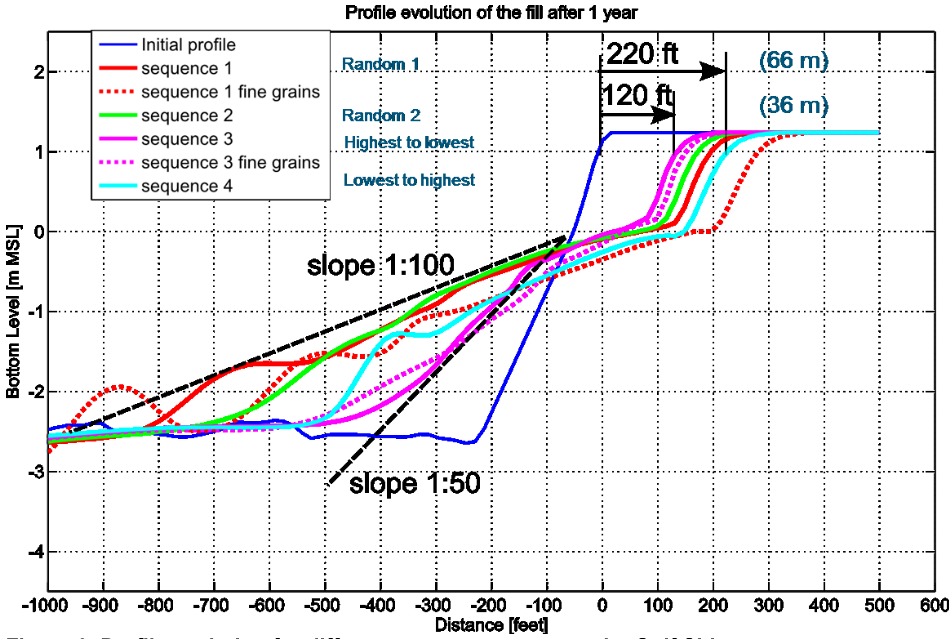


Figure 8. Profile evolution for different wave sequences at the Gulf Side

The simulated cross-shore profile evolution was compared (see Fig. 9) with the empirical Dean (1977) profile and with an actual cross-shore profile at West Ship Island. The Dean profile and the West Ship Island profile are, except for the beach area, very similar. The cross-shore profile resulting from sequence 3 calculated with UNIBEST-TC shows similarity in the slope between 0 and 500 feet with both the Dean profile and the actual West Ship Island profile.

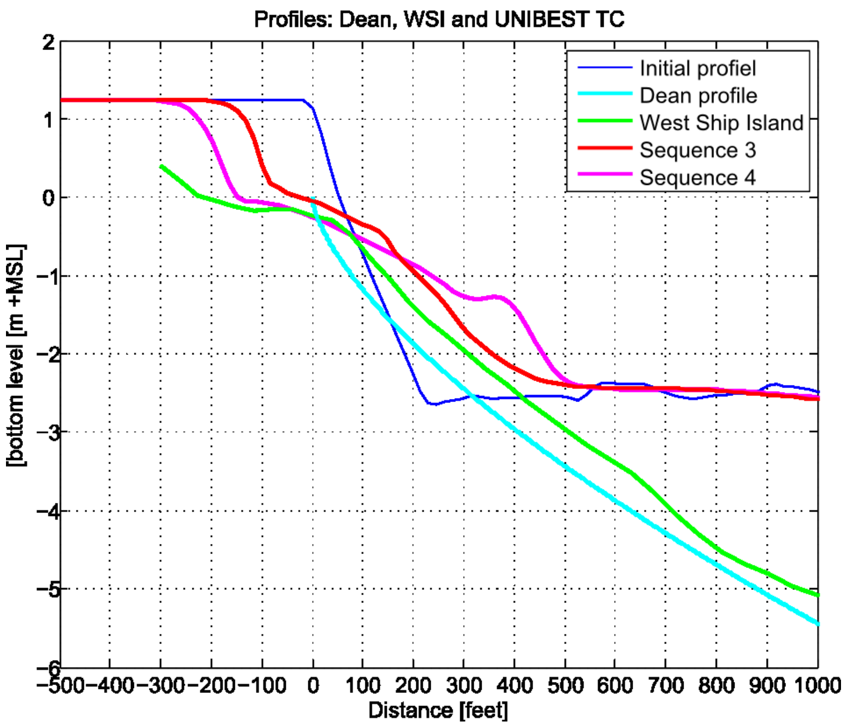


Figure 9. UNIBEST-TC results (sequence 3 and sequence 4) compared with empirical Dean profile and West Ship Island Beach profile

The analysis of the profile evolution after one year (see Fig. 10) leads to the conclusion that the initial profile has been selected sufficiently wider than the expected range of possible erosion due to waves and tides, and there is no risk of breaching provided that no tropical storms or hurricanes occur.

Furthermore, most of the sediment eroded from the upper part of the profile will remain within the footprint of the final design template.

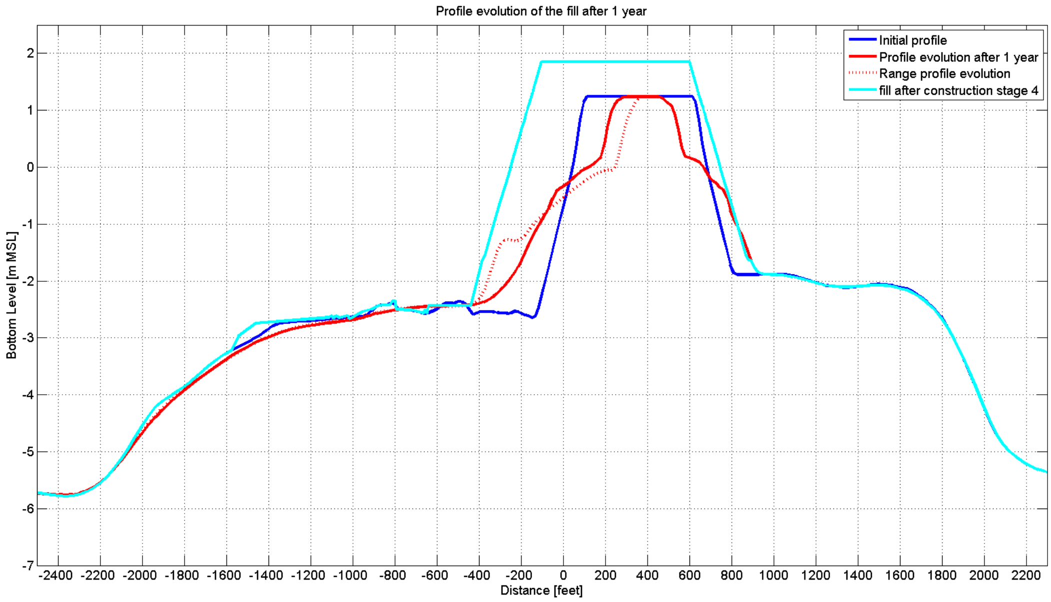


Figure 10. The expected range of profile evolution after one year

TURBIDITY PLUMES

A hopper dredge pumping a slurry of sand and water to the breach will cause a local increase of turbidity by dispersion of fines. Directly north of both West and East Ship are highly sensitive areas of sea grass (see Fig. 11) where a significant decrease of light attenuation over an extended period of time due to increased turbidity could result in adverse impacts. The limit of turbidity as set by state water quality standards of no more than 50 NTU above background was used in the evaluation of construction related turbidity extents. Laboratory analysis of the sediments collected near Ship Island showed that this is equivalent to a sediment concentration of 0.087 g/l.

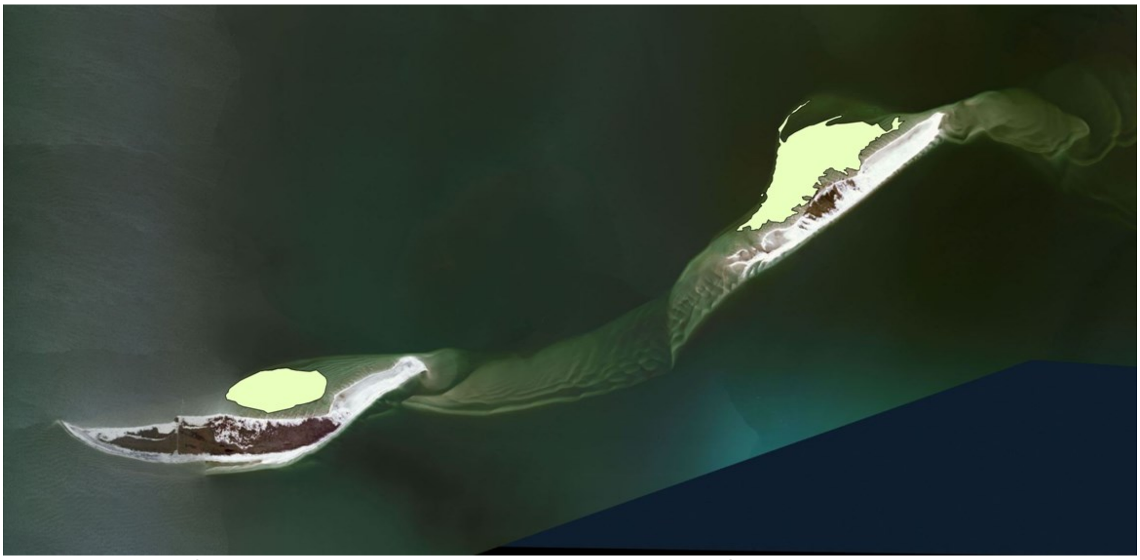


Figure 11. Indication of the sensitive seas grass areas at East and West Ship Island (green colored areas indicate the sea grass).

Analysis of samples from the borrow area revealed that the sediments have a fines content varying between 7-9%, with a few samples having upwards of 13% of fines. In the model simulations, three fractions of fines were defined (see Table 1). A conservative assumption was adopted that all fines would be released to form a turbidity cloud (in practice, a significant part of fines remains "encapsulated" in the slurry and do not contribute to the increase of turbidity).

Table 1. Classification of fine sediment used in model simulations

Sediment Classes	D50 (μm)	Percentage	Discharge of fines; closure from East to West (kg/m^3)	Discharge of fines; closure from West and East (kg/m^3)
Fines 1	50	5%	136.40	68.20
Fines 2	30	3%	81.84	40.92
Fines 3	10	1%	27.28	13.64

The impact of the turbidity plumes during placement of dredged material at the head of the fill was examined using the sediment dispersion model in Delft3D. The simulations covered the full neap to spring tidal cycle. It was shown that the during the neap tide conditions, the turbidity plume occupies the largest area with the highest concentrations, due to less energetic conditions causing less plume dispersion than during the spring tide. The 50 NTU limit is exceeded, however this occurs at a safe distance from the sea grass areas (see Fig. 12).

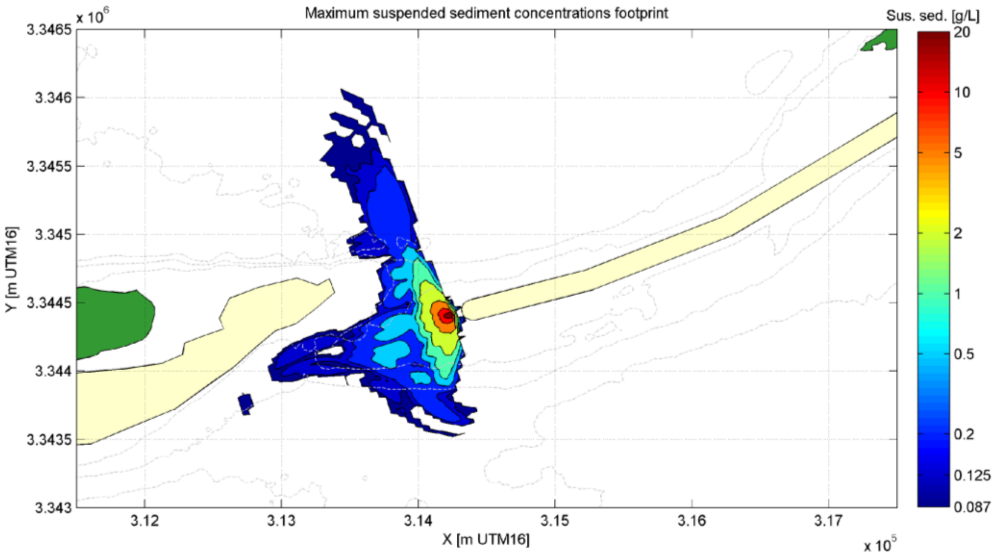


Figure 12. Maximum excess suspended sediment concentrations for the Closure from East to West scenario (green colored areas indicate the sea grass).

Besides the maximum suspended sediment concentration footprints the time period during which the critical suspended sediment concentration is exceeded was also considered. Long periods of high sediment concentrations/low light intrusion in the water column are likely to result in more negative environmental effects. In Fig. 13 the exceedance times in percentage of the critical value of 0.087 g/l for the East to West closure scenario are given based on a simulated two-week period. Suspended sediment concentrations exceed the critical value of 0.087 g/l more than 2% of the time (i.e. a total of approximately 6.5 hours in 14 days) only in the vicinity of the Ship Island breach fill.

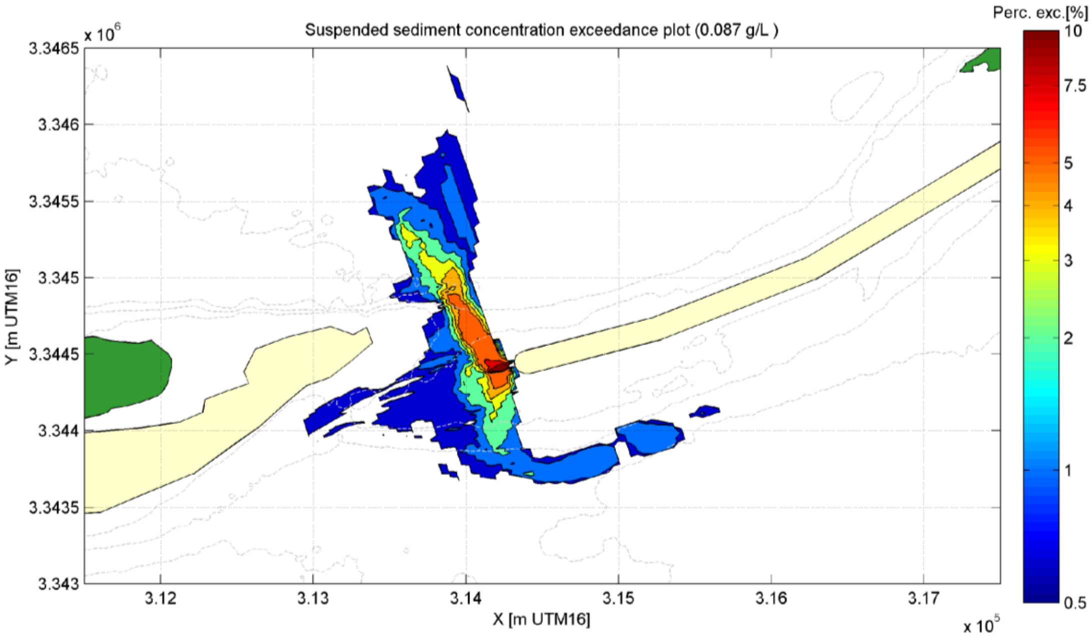


Figure 13. Excess suspended sediment concentration exceedance plot in percentages for 0.087 g/L, Scenario East to West (green colored areas indicate the sea grass).

A sensitivity analysis was carried out, to establish the influence of variation in the wave conditions, higher (13%) fine sediment content, higher production capacity (use of a larger hopper dredge), and variation on numerical parameters. It was found that the area of sea grass would be influenced by high turbidity only under exceptional conditions (Fig. 14). With the results of simulations, protection measures can be determined to mitigate potential environmental impact.

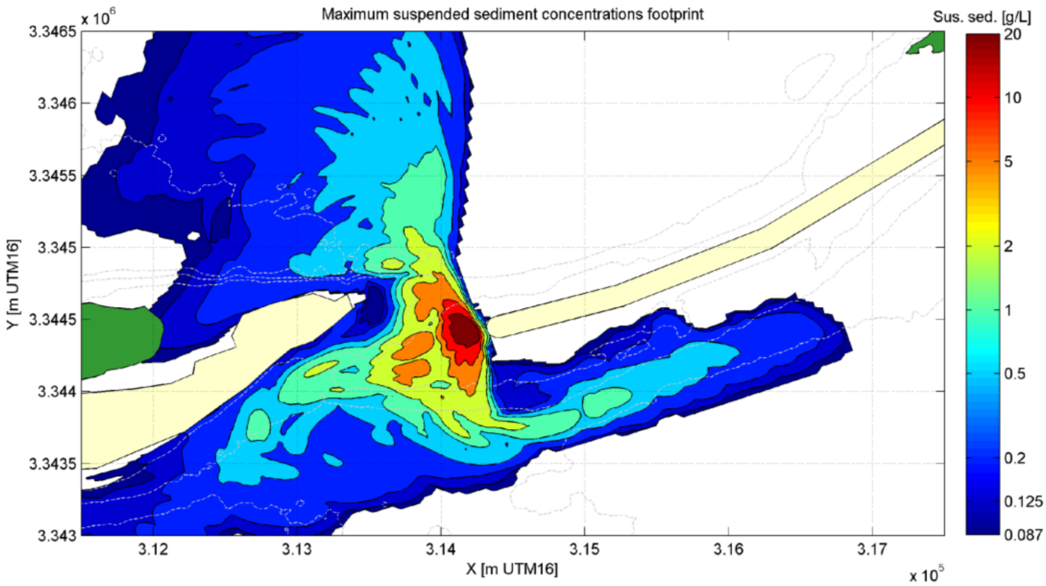


Figure 14. Maximum excess suspended sediment concentrations for the East to West scenario for fine sediment distribution (13% fines) (green colored areas indicate the sea grass).

CONCLUSIONS

The method applied in this project, incorporating advanced computer models in the design process, provided reliable and robust information to optimize the construction procedure whilst minimizing its adverse impacts.

The conclusions of the study can be summarized as follows:

1. The closure strategy from East to West, initially adopted by USACE, is confirmed to be the optimum strategy.
2. Sediment loss from the initial profile (Phase 1 fill) remains within acceptable limits.
3. Production of the hopper dredge is sufficient to close the gap.
4. Risk of breaching of the initial (Phase 1) profile is negligible provided that no tropical storms or hurricanes occur in the first year of works.
5. Turbidity limits are likely to be exceeded, but far away for the sea-grass areas.
6. If high content of fines is allowed, the turbidity limits are likely to be exceeded also in the sea-grass areas; monitoring and protection measures will be required in this case.

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