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Land Barrier preliminary design

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May 2016

TU Delft

Royal HaskoningDHV
Enhancing Society Together

Defacto
Urban & Landscape design

Galveston Bay Area

Land Barrier preliminary design

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Summary

Over the past decades, the millions of people and numerous businesses around the Galveston Bay have experienced the consequences of living in a hurricane-prone region. The area around the bay is characterized by marshlands in the east and large urban areas in the west, most notably the city of Houston. The Galveston Bay itself is separated from the Gulf of Mexico in the south by two land masses, namely Galveston Island and Bolivar Peninsula. In 2008, these low-lying islands were completely overrun by a 4-5 meter (12-14 ft.) storm surge caused by Hurricane Ike. The surge and high waves flooded large parts of the Galveston Bay Area. The main path of impact just missed the centre of Houston and the port of Houston, one of the largest petrochemical harbours in the worlds. The devastation following Hurricane Ike – with over $25 billion of damage and a hundred deaths already the most expensive storm in Texas' history – triggered several research initiatives for a bay-wide flood defence system.

Possible alternatives include a plan to shorten the shoreline with land barriers and storm surge barriers with the 'Ike Dike' (or Coastal Spine). Other initiatives focussed on the protection of the port by constructing storm surge barriers in the northern part of the bay ('Upper Bay solution') or protecting the western part of the bay by dividing the bay in two ('Mid Bay solution'). All mentioned alternatives include the construction of a land barrier on Galveston Island and Bolivar Peninsula. This report elaborates on previous research and the many options in terms of location, safety standard, height and structural composition. It focusses on one of the possible solutions and provides basic dimensions of a land barrier capable to protect the region from hurricane disasters, based on recent hydraulic data.

Basis of the design

The design aims to provide a solution with a safety level of 1/100 year^{-1}. The corresponding hydraulic data have been modelled by Almarshed (2015) and add up to a storm surge of 4.7 meters (15.4 ft.) with waves of 6.9 meters (23 ft.) at an offshore location. The storm surge is assumed to increase up to 5.7 meters (18.7 ft.) due to sea level rise. These figures are used in SWAN-analysis in order to compute the nearshore conditions. Especially the significant wave height decreases greatly when the conditions near the shore – or even inland – are considered. The nearshore wave conditions are shown in Table 1.

Table 1 - Offshore and nearshore conditions as used for the land barrier design

		Offshore (32 km)	At shoreline	Inland (100m)	Inland (>200 m)
Maximum surge	[m+MSL]	4.7 m	4.7 m	4.7 m	4.7 m
Sea level rise	[m]	1.0 m	1.0 m	1.0m	1.0m
Bottom level	[m+MSL]	-16 m	-1.4 m	+1.5 m	+1.5 m
Wave height H_s	[m]	6.9 m	3.2 m	2.2 m	1.9 m
Wave period T_p	[s]	13.7 s	13.7 s	13.7 s	13.7 s

An important technical boundary condition is the allowable overtopping rate. Reference projects in the Netherlands and New Orleans are usually designed for overtopping rates of 1 to 3 l/s/m. However, because of the large storage capacity of the Galveston Bay, a higher overtopping rate can be applied. For this land barrier design, an overtopping rate of 50 l/s/m is used. This does limit the options for materials and spatial design and can lead to progressive erosion of the embankment.

Spatial analysis

The landscape across Galveston Island and Bolivar Peninsula varies greatly in terms of land use and population. To get an understanding of the main characteristics and their respective locations, Galveston Island and Bolivar Peninsula are divided into a number of cross sections. These cross sections vary based on population and their location in respect to the main road. The following map shows the large variation along the length of the land masses, and Galveston Island in particular. Bolivar Peninsula shows a lot of open landscape, which is relatively easy to design for. However, long stretches also show a cross section (D in Figure 1) where a lot of people live between

the Gulf of Mexico and the main road. Galveston Island also shows several pieces of open landscape and the Galveston Seawall, which is outside of the current scope. The challenge lies particularly in the long stretches of land where the main road is close to the shore (C in Figure 1) The main residential area is located at the bay-side of the

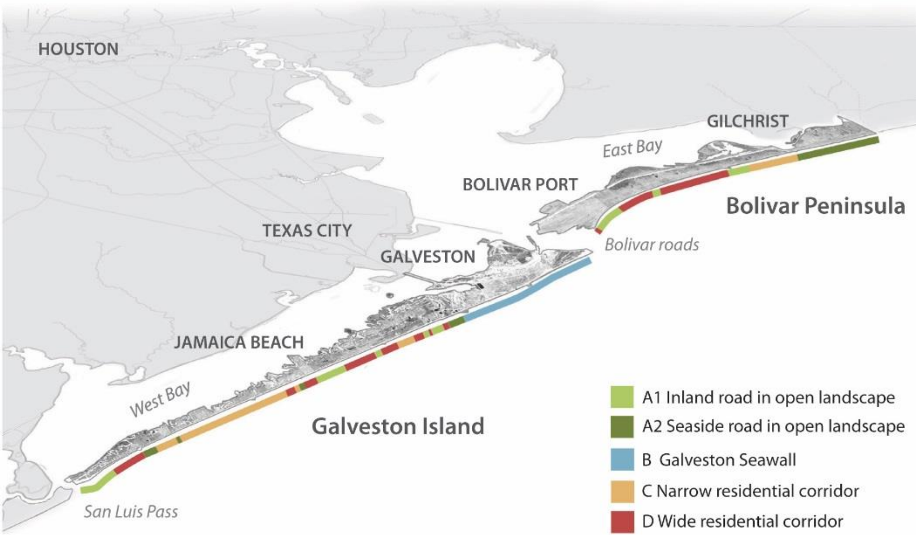


Figure 1 Overview of Galveston Island and Bolivar Peninsula divided into characteristic cross sections

These two cross sections – C and D from Figure 1– are viewed as the most challenging and will as such be designed for representing Galveston Island and Bolivar Peninsula.

Land barrier design

This design covers the location, main dimensions, construction material and estimated costs of a land barrier capable of significantly reducing the flood risk for the areas around Galveston Bay, including Galveston Island and Bolivar Peninsula.

The current location of the **main roads (FM3005 and SH87)** is chosen as the preferred land barrier location, as opposed to the coast. The main reason is the interference of a barrier at the coast in the coastal system and the associated increased maintenance costs. Moreover, the crest of a barrier at the road is lower, as shown in Table 1. Also, the view on the beach remains when driving on the road and it offers a robust evacuation route. A downside of this placement is the remaining vulnerability of houses living on the Gulf-side of the main roads, which affects an estimated 34% and 64% of the residents on Galveston Island and Bolivar Peninsula, respectively.

Technical calculations - based on widely-used design manuals – show a required crest height of **7.8 meters (26 ft.) and 7.4 meters (24 ft.)** on Galveston Island and Bolivar Peninsula respectively. A core of clay is chosen because of the wide availability and relatively low costs. In order to structurally maintain a barrier of this height during design conditions, a strong armor layer is needed to protect the core. An indication of the structural composition of the land barrier is shown in Figure 2.

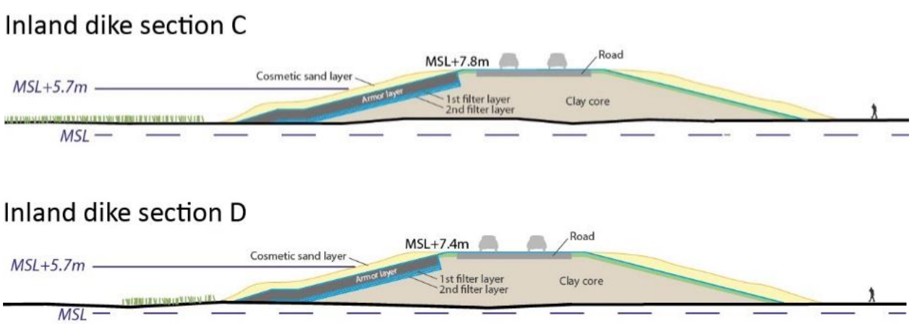


Figure 2 – cross section and main structural components of the land barrier

A soil-based structured, protected by a non-natural armor layer (e.g. rock, asphalt, concrete), will be a sharp and unappealing division of the land masses. Therefore, the land barrier will use the **'dike-in-dune'-concept**, which has already been implemented successfully in the Netherlands and United States. The revetment covering the clay core will in turn be covered with a sand layer. This will ensure a natural and more appealing integration in the landscapes of Galveston Island and Bolivar Peninsula. The natural layer is assumed to have no protective value and will need repair or replacement after heavy storms. The main concept is visually described in Figure 3.

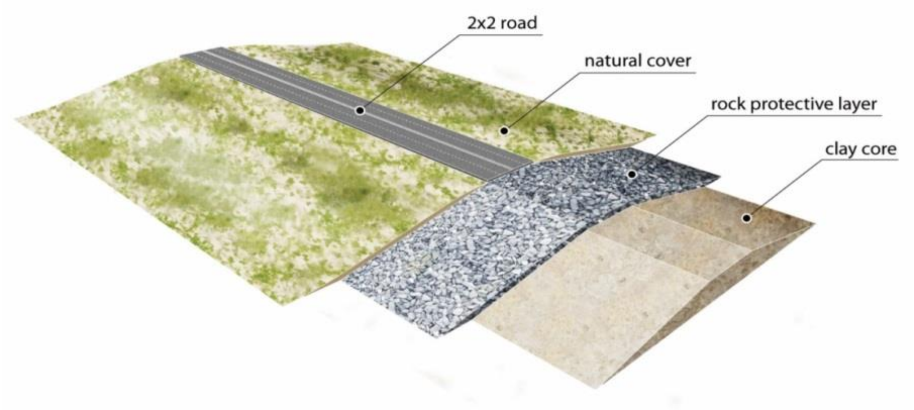


Figure 3 - main concept of the 'Dike-in-dune' land barrier design

The costs of the land barrier can only be estimated with large uncertainty in the current stage of design (±50%). The costs account for a land barrier with a natural layer of **74 km (50 miles)** from San Luis Pass on Galveston Island up to High Island on the other side of Bolivar Peninsula. Any connections to high grounds are not included. Neither are costs for maintenance, road construction or buyouts.

The total estimated costs for the proposed land barrier are **USD 2.3 billion** (+/-50%), which is **31 M$/km**. For comparison, the total costs of a similar barrier at the coast are roughly 50% higher at USD 3.5 billion (+/-50). The difference is mainly due to the relatively low crest height, smaller berm and lighter revetment of the proposed barrier.

Land barrier ends

Early models – which placed a land barrier from San Luis Pass up to High Island – showed large flooding of natural refuges at both sides of the barrier. This is a result from the storm surge flowing around the barrier. The exact ending of the land barrier will greatly influence the project costs and the risk reduction resulting from construction of the land barrier. This research included two options for both ends of the barrier.

At the western end, an extension of the land barrier along the coast (Bluewater HWY, CR-257), in combination with a barrier at San Luis Pass is preferred over an inland connection. It does not interfere with nature reserves and does not require storm surge barriers other than San Luis Pass-barrier. If a barrier is needed at all - from a system flood defence standpoint - should be subject of future research.

At the eastern end, an inland barrier along the SH124 towards Stowell seems the preferred option over a coastal (former SH-87) barrier. The road is shorter (25 km, 15.5 miles), gradually runs towards high ground and is therefore estimated to be much cheaper. Also here the necessity of the barrier requires further research.

Many parts of the design and the exact role of the land barrier in the total flood defence system remain unknown and require additional research. However, past hurricane events and the subsequent models have shown the necessity of large-scale solutions. A strong and resilient land barrier on Galveston Island and Bolivar Peninsula will create a first line of defence as a crucial part of the total system protecting the Galveston Bay Area.

Contents

1 Introduction

1.1. Purpose of this report

The highly populated Galveston Bay Area is located in the eastern part of Texas, USA. This region is at significant risk from hurricane-induced flooding, as became clear during Hurricane Ike in 2008. Since then, several research initiatives have focussed on preventing future hurricane disasters. Over the past years, the TU Delft has assisted in the design of a flood defence system to protect the Galveston Bay Area.

The different solutions that are currently proposed all incorporate a land barrier into their flood defence system (SSPEED 2015). This report summarizes the first conceptual design efforts for the land barrier on Galveston Island and Bolivar Peninsula and identifies the future design challenges.

This research follows from a collaboration of TU Delft, Defacto and Royal HaskoningDHV (RHDHV), with contributions from Texas A&M University and SSPEED Center. A special part of the design process is the 'Land barrier design workshop', which was held January 14th, 2016 at TU Delft, the Netherlands. During this workshop, experts from a variety of research fields assessed the design alternatives of the land barrier in a broader perspective.

1.2. Galveston Bay Area project overview

The Galveston Bay Area is characterized by a great variation of land-use in a low-lying region. The eastern part of the bay primarily consists of marshland, while the western part is home to millions, mostly concentrated in the city of Houston. Other notable locations around the Galveston Bay are the city of Galveston - at the eastern tip of Galveston Island - and the Port of Houston, which hosts one of the largest petrochemical complexes in the world.

When Hurricane Ike hit, it made landfall at Galveston. This meant that the most destructive side of the hurricane hit the easterly marshlands with a low density of population and industry. The damage was still significant at $25 billion in economic loss and more than 100 fatalities. However, several models show that a more western landfall location would expose Houston and its port to the more destructive side of the hurricane. This would lead to a far more catastrophic event in terms of economic loss, fatalities and ecological impact (SSPEED 2015).

Figure 4 - Overview of the Galveston Bay Area (Source: SSPEED)

The bay is separated from the Gulf of Mexico by two land masses, Galveston Island and Bolivar Peninsula. During Hurricane Ike, the low-lying land masses (maximum elevation of 1.5-2m, 5-7 ft.) were completely overrun by the storm surge, which could run up to 4-5 meters (12-14 ft.). Hurricane Ike brought the topic of flood protection to the forefront of local attention. Prof. Dr. William Merrell of Texas A&M University at Galveston (TAMUG) proposed an artificial coastal barrier called the 'Ike Dike' in order to protect the region from flooding as a result of hurricanes. This Ike Dike closes off the bay from the Gulf of Mexico with land barriers on Galveston Island and Bolivar Peninsula and storm surge barriers in Bolivar Roads and San Luis Pass.

Another solution focusses on protecting the Port of Houston with storm surge barriers in the upper part of the bay instead of Bolivar Roads (the 'Upper Bay'-solution). A third option includes a part of the highly populated western side by separating the bay in two parts (the 'Mid Bay'-solution). Although the locations of the storm surge barriers vary, all three of these options include the construction of a land barrier on Galveston Island and Bolivar Peninsula. This barrier should limit the water flowing into the Galveston Bay, leading to a significant decrease of surge and in turn a decrease of expected damages and losses.

1.3. Earlier studies

Much research has been conducted over the years on the designs of different flood defence components, primarily focussing on the Ike Dike (later referred to as 'Coastal Spine'). With this in mind, the Coastal Spine design report was drafted in June 2015 to summarize the research on different components of the flood defence system.

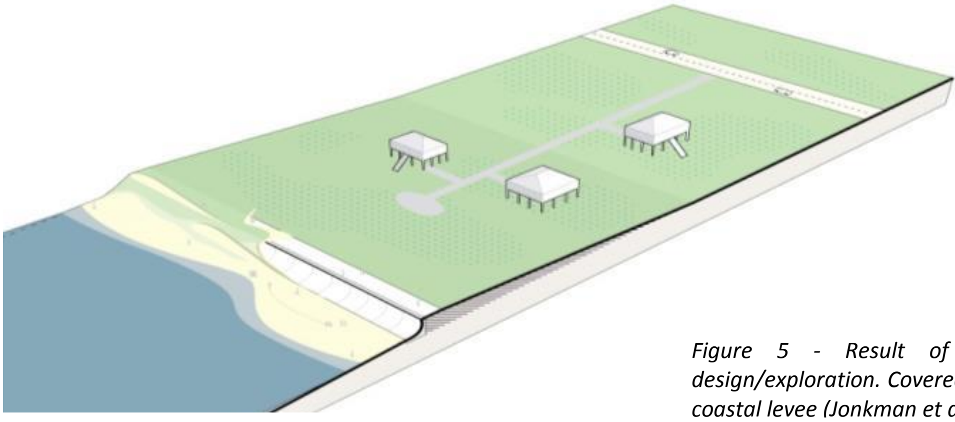


Figure 5 - Result of the initial sketch design/exploration. Covered sea wall with a wide coastal levee (Jonkman et al. 2015)

The report (Jonkman et al. 2015) includes a preliminary design of the land barrier and three storm surge barriers which were part of the initial flood defence system. The design showed a (locally covered) extended seawall as a preferred alternative, which will also be discussed later in this report. An initial cost estimate showed that the land barrier is responsible for 40% of the total costs of the Coastal Spine system. The land barrier is still in a conceptual design phase while other elements of the Coastal Spine system have been designed in more detail. This report presents a more elaborate design and research of the land barrier.

1.4. Report structure

The chapters in this report match the steps taken in the design of the land barrier on Galveston Island and Bolivar Peninsula. **Chapter 2** presents the basis of the design. This includes hydraulic boundary conditions, design requirements and calculations methods. A spatial analysis is included in **Chapter 3. Chapter 4** shows the technical alternatives that have been developed, based on the boundary conditions from chapters 2 and 3.

Subsequently, **Chapter 5** summarizes other relevant investigations that have been conducted during the design phase, which clarify other aspects, related to ecological- and legal impact and the impact on the coastal system. The findings from other research may be used in the choice of a preferred design. Lastly**, Chapter 6** elaborates on the choice for the preferred design and explains its pros and cons and suggestions for additional research. More technical information is included in the appendices.

2 Basis of the design

The land barrier is designed based on a chosen protection level together with a required service life. The protection level corresponds to a combination of hydraulic boundary conditions that the system should be able to cope with. The level of safety is characterised by a certain yearly probability of exceedance of the conditions linked to that situation.

The land barrier will be designed with a design service life of 100 years and a protection level of 1/100 per year. In other words, the structure shall be able to withstand the hydraulic conditions with an average return period of 100 years. It must do so until the end of its design service life. This is a common service life for soil-based flood defence structures. In this design, the barrier crest height will be designed for the combination of surge and waves. The only failure mechanism that will be designed for in this design stage is overtopping. An analysis of the overtopping limits can be found in Chapter 2.2.

2.1. Hydraulic boundary conditions

There are several (ongoing) studies on the hydraulic boundary conditions for the Galveston Island/Bolivar Peninsula shoreline (Jin et al. 2012; Lendering et al. 2014; Stoeten. 2013; Sebastian et al. 2014). The offshore conditions for this design are based on the most recent findings of Almarshed (2015). This research analysed the wave conditions for a buoy located 32 km from the Bolivar Peninsula shoreline. The assessment is based on an Extreme Value Analysis of historical data. Almarshed (2015) mentions the significant wave height at the buoy location for different return periods.

These offshore wave conditions do not take into account any nearshore effects, such as shoaling and wave breaking. Because of these effects, the nearshore conditions differ significantly from the offshore conditions. As the water depth at the land barrier is lower than the breaking water depth, the highest possible waves will not reach the land barrier with all their energy. A one-dimensional SWAN model was set-up to assess the propagation of a hurricane-induced wave. The model shows different values for the significant wave height, depending on the water depth.

The table below shows both the maximum water surge and peak wave period as derived by Almarshed (2015). It also shows the significant wave height, which results from the SWAN model based on the significant wave height at the buoy and the local bottom level. Refraction and diffraction are not taken into account. An in-depth analysis of the offshore- and nearshore conditions can be found in Appendix A. Several considerations and limitations of the SWAN model are also added. The potential impact of beach erosion and other coastal sediment transport has not yet been investigated at the time of this research.

Table 2 - Hydraulic boundary conditions for the land barrier design

	Buoy (32km offshore)	**100m seaward**	**At shoreline**	**Island (100m inland)**	**Island (>200m inland)**
Maximum water surge in Gulf* (m+MSL*)	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m
Sea level rise (m)	1.0 m	1.0 m	1.0 m	1.0 m	1.0 m
Bottom level (m+MSL)	-16 m	-1.4 m	0 m	+1.5 m	+1.5 m
Significant wave height (H_s)	6.9 m	3.4 m	3.2 m	2.2 m	1.9 m
Peak wave period (T_p)	13.7 s	13.7 s	13.7 s	13.7 s	13.7 s

**MSL = Mean Sea Level, equal to 1.15 m+NAVD88*

Sea level rise

Due to the design service life (100 years), the situation for 2116 is used for design. Therefore maximum water surge should include sea level rise over this period. Sea level rise is estimated to be 1.0m (3 ft.) in 100 years and is based on De Vries (2014). An alternative – also used in New Orleans – is to partly adapt to sea level rise, while making the barriers adaptable. The barrier will not have to be built at the same height and a closer look during the coming years will have to decide whether further heightening is necessary. This form of optimization has not been used in this design, but is recommended for later work.

Protection level

This design assumes a 1/100 year^{-1} protection level. This choice is mainly based on common practice in the US and its validity has been subject of discussion in earlier studies (Jonkman et al. 2015). These studies showed, with Dutch experience as reference, that higher protection levels could be economically desirable. Further research towards the economically optimized protection level has not yet been conducted and is highly recommended.

As an indication of the impact of a different protection level, Almarshed (2015) provides the extreme storm surges and significant wave heights for different return periods.

Table 3 - Extreme storm surges and significant wave heights for different return periods (Source: Almarshed 2015)

Return period (years)	**Extreme storm surge**		**Extreme H_s (32 km offshore)**	
	[m]	[ft.]	[m]	[ft.]
10	2.1 m	6.9 ft.	4.7 m	15.4 ft.
50	4.0 m	13.1 ft.	6.2 m	20.3 ft.
100	**4.7 m**	**15.4 ft.**	**6.9 m**	**22.6 ft.**
200	5.6 m	18.4 ft.	7.6 m	24.9 ft.

2.2. Overtopping

The table below shows several limits for the mean discharge over seadikes and seawalls. Generally, dikes in the Netherlands and New Orleans are designed for overtopping rates of 1 to 3 l/s/m. For this location, a higher overtopping rate seems more suitable, because the Galveston Bay is sufficiently large to store this overtopping volume. Furthermore, a large part of the risk of flooding is prevented when the forerunner does not enter the Galveston Bay. Therefore, an overtopping rate of 50 l/s/m, which could lead to progressive erosion of the embankment, is allowed in this case. This is applied for both the land barrier on Galveston Island and Bolivar Peninsula. To provide insight into the required dimensions of an overflow resistant barrier, the 200 l/s/m and 600 l/s/m cases - which require additional measures at the inner slope - are also presented.

Hazard type and reason	**Mean discharge (l/s/m)**	**Mean discharge (ft^3/s/m)**
Limited damage to inner slope (fully retaining barrier)	1	0.035
No damage to crest and rear face of grass covered embankment of clay	10	0.35
Limited damage to crest and rear face of grass covered clay embankment	50	1.76
No damage if crest and rear slope are well protected	200	7.1
Extreme overtopping, major damage is accepted after a 1/100 yr^{-1} storm. Additional measures required for drainage on rear side.	600	21.2

Table 3 - Limits for overtopping for damage to the defence crest or rear slope (modified from Eurotop, 2007)

2.3. Design formulas

For the seadike calculations the TAW2002a overtopping method is used, see Rock Manual section 5.1.1.3 pages 506-510 (CIRIA, 2007). The vertical wall calculations are based on Design overtopping of Seawalls; Design and Assessment Manual (HR Wallingford Ltd., 1999).

2.4. Concluding remarks

The design will be based on the hydraulic boundary conditions and overtopping rules stated above. The following considerations should be kept in mind:

- The amount of water that can be stored in the Galveston Bay before any inconveniences occur depends on the total flood defence system. The allowable overtopping limit - which is directly linked to the height of the barrier - can therefore change depending on different region-wide flood defence systems.
- Sea level rise has a large impact on the required barrier height. The main wish is to construct as low as possible, in terms of crest height. This design uses a conservative estimate for the sea level rise over the entire service life. As stated before, it is possible to heighten the barrier for sea level rise in stages. For example, one could construct for 25 years of sea level rise. During large maintenance moments 15-20 years from now, the barrier can be heightened further (if necessary). In any case, more research on sea level rise in the region is recommended.
- The Galveston Seawall is currently constructed at 17 feet (5.2 meters). This is slightly higher than the current 1/100 per year storm surge. When sea level rise is included, the design storm surge even surpasses the crest of the Galveston Seawall. In this case, the situation changes from extreme overtopping into overflow, which results in an enormous increase in water volume crossing the crest of the seawall. The concrete barrier and the urban environment behind it are able to withstand significant amounts of water. However, more research on the current – and future - safety level of the Galveston Seawall is highly recommended.

Both the hydraulic boundary conditions and the chosen protection level are based on several assumptions which need additional research. The presented numbers are a reasonable approximation of research done on the 1/100 per year storm conditions. Future changes in hydraulic boundary conditions could lead to other potential alternatives and recommendations.

3 Spatial analysis

The majority of the project area's shoreline is developed, though currently without flood protection infrastructure. The land barrier will have to be fitted in the existing spatial context, which might interfere with current land uses, e.g. the many residential areas along the shore. The spatial configuration and character varies strongly along the shores of the research area. The Galveston Island and Bolivar Peninsula shoreline is interspersed with buildings and infrastructure, although there are open stretches to be found as well.

This section provides a better insight in the spatial context of the potential locations for the land barrier. A series of typical cross sections is explored, each of which is representative for one or more stretches along the shore. Ultimately, two specific design cross sections are identified for further use in the technical design of the land barrier.

3.1. Spatial structure of the project area

Galveston Island

Galveston Island is linearly shaped and enclosed by the Gulf of Mexico and West Bay. The city of Galveston is the main urban area of the island and is connected to the mainland through the interstate-45 bridge. The rest of the island is disclosed by FM3005 (San Luis Pass Road) that runs over the island's shores in parallel with the coastline from Galveston to the San Luis Pass in the east. Here a second bridge connects the Galveston Island to Follets Island and Freeport. The various residential areas along the island are connected to the City of Galveston through this main traffic artery.

Galveston city has its own typical seafront in which the Seawall separates the city from the beach and the sea. This is different from the non-urbanized part of Galveston Island, where properties have been placed close to the beach. Most of this side of Galveston Island's shoreline has been developed with holiday beach homes, which are organized in communities. On the bay side, long stretches of natural marshes are found sparsely built with holiday homes as this side of the island is far less developed. In general the open landscape is uncultivated, several (state) parks can be found on the island.

Bolivar Peninsula

Bolivar peninsula is less populated and less developed compared to Galveston Island. It is somewhat secluded as it only has a road connection to the mainland on the northeast and a ferry connection to Galveston Island. The peninsula is wider than Galveston Island and is characterized by its undeveloped plains and marshes, long-stretched beach and small communities like Port Bolivar, Chrystal Beach, Gilchrist and Caplen. The residential areas are lined up along the beach or Galveston Bay and East Bay on the other side of the land mass and are connected through State Highway 87. The population density in these communities is relatively low, and the properties have lower value compared to those on Galveston Island.

3.2. Characteristic cross sections

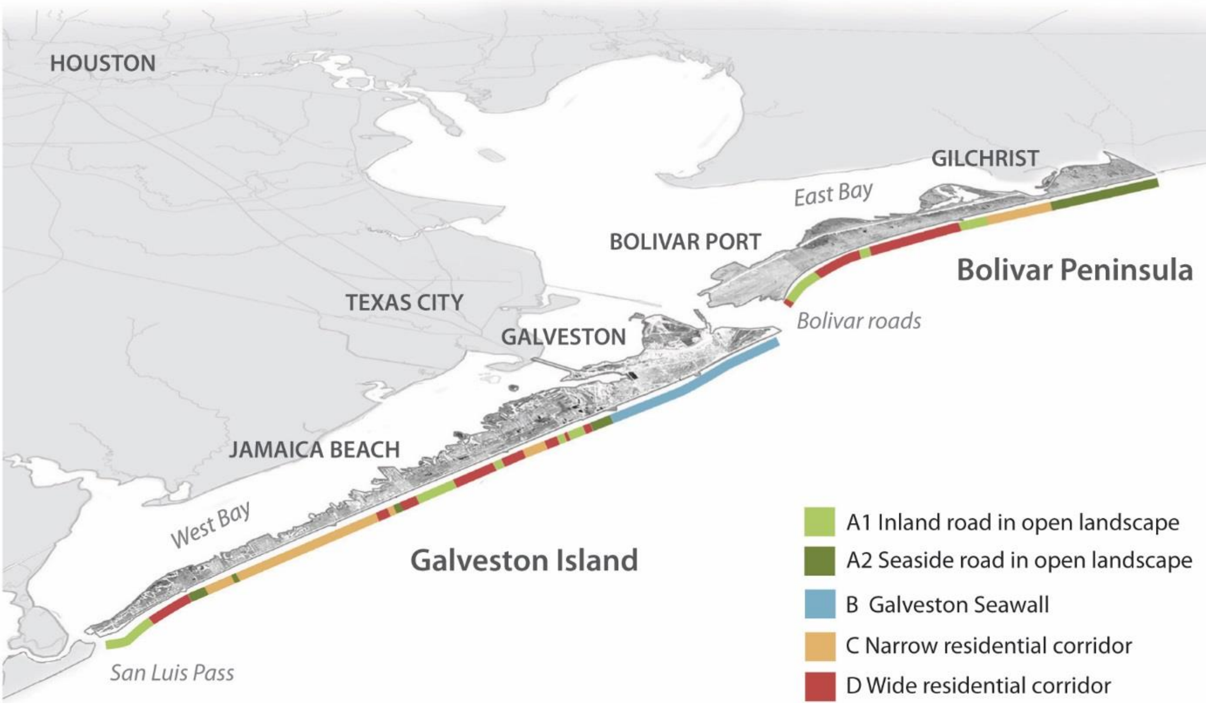


Figure 6 - Stretches represented in the characteristic cross sections

The shores of Galveston Island and Bolivar Peninsula can roughly be structured in four typical spatial configurations. For each of these types the organization of infrastructure, buildings and geographic characteristics sets a distinct spatial context for the design of the land barrier. The sections represent multiple stretches along the shore. Figure 6 indicates where stretches of the representative cross sections are located within the project area. The following paragraphs discuss the four characteristic cross sections.

In Appendix B, two possible infrastructural plans are mentioned for cross sections C and D: The first with a single two-way road and the second with separate roads. Cross section A is also divided in two possibilities, based on road placement. In all instances, a double road will leave more space for placement of a flood defence structure. This means that the 'single road' infrastructure plan will be more critical and will therefore be used as representative for their respective configuration.

A. Road in open landscape

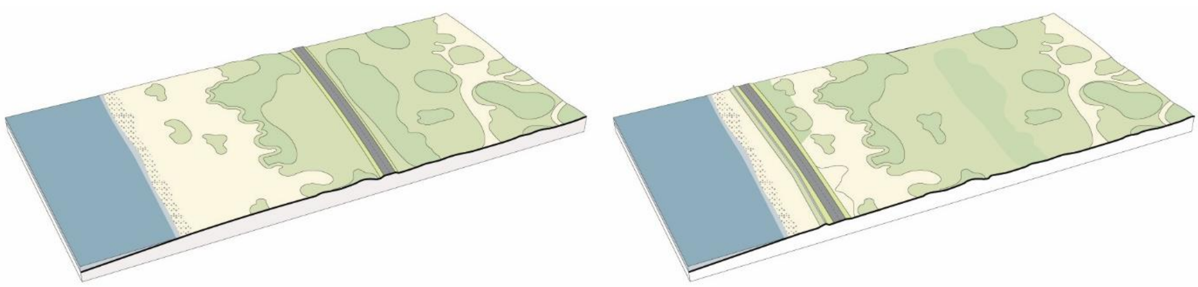


Figure 7 - Characteristic cross sections: A1 Inland road in open landscape; A2 Seaside road in open landscape

Section A comprises the undeveloped areas along the shore, and comes in two sub-types. In type A1 the beach and dunes continue relatively far inland. The open landscape comprised of low dunes (south of the road) and plains (north) is crossed by the main road, which is located at a relatively large distance from the shoreline (350 – 550m or

0.2 – 0.3 mi). As the area is absent of buildings, trees or large sized shrubbery, people experience a panoramic view of the island including the beach when driving on the road. This cross section is representative for some small stretches of Galveston Island and Bolivar Peninsula.

Type A2 is only found on the shores of Bolivar Peninsula, at the eastern edge of the project area near High Island. In this section, the main road runs directly along the shoreline, over the dunes, secluding the beach from the hinterland. The seclusion is caused by both a lined ditch along the northern edge of the road is, as well as Jersey barriers along the beach-side to the south of the road which limits the entrance to the beach. The Jersey barrier line is opened every 500– 1000m (0.3 – 0.6 mi) for traffic to enter.

From a spatial perspective there are no elements in these sections that constrain the land barrier's footprint. The width of the main road varies between 10 – 13m (33 – 43ft.). The road's parcel width is approximately 30m (100ft.).

B. Galveston Seawall

Figure 8 - Characteristic cross section: Galveston

The Galveston Seawall runs directly in front of Galveston city in a continuous stretch of approx. 16 km (10 mi). Although the seawall itself is uniform, its character can best be described in three sections – west, centre and east. The seawall's western section runs in front of Scholes international airport from San Luis Pass road to 61st street. It is constructed directly in the shoreline, in direct contact with the Gulf of Mexico without the presence of a beach. The seawall's crest holds "Seawall Boulevard", a wide city road of about 30m (100ft.) that runs along its complete length.

Moving further eastward from 61st street, groins are constructed every 300m (1000ft.), retaining sand to form a small beach of approx. 35m (115ft.) wide. The seawall is partly covered but still visible, protruding 2m (6ft) above the beach. On the northern side, the Seawall Boulevard is lined with hotels, restaurants and shops which benefit from the attractive view over the Gulf of Mexico, the beach and the Galveston Island Pleasure Pier. Only sporadically some palm trees are found along the northern side of the boulevard, whilst there is only little greenery found along its complete stretch. The properties along the Boulevard are constructed at level. As a connection between the Boulevard and Galveston's grid street plan, the landscape's elevation is pitched downwards until it reaches mean ground level after 100m (330ft.) from the seawall crest.

Further to the east, the seawall diverts from the shoreline, directed more to the island's centre until arriving at Bolivar Roads where they abruptly end. As the seawall retracts from the shore, the beaches grow into a large spit, holding East Beach/Appfel Park, a popular tourist destination, and some large hotels.

C: Narrow residential corridor

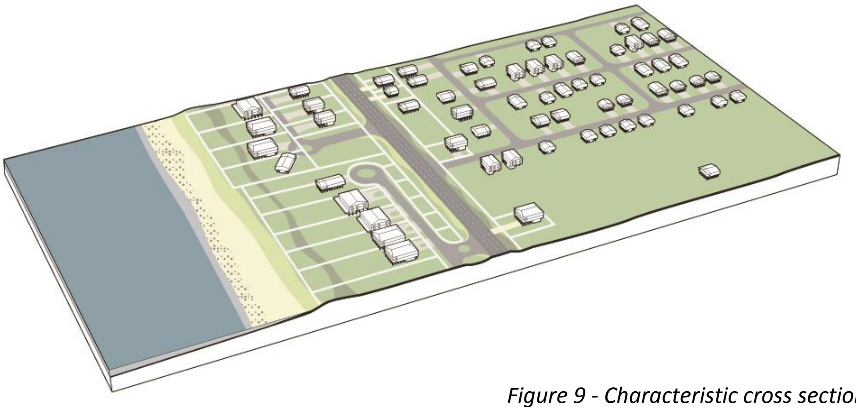


Figure 9 - Characteristic cross section for C: Narrow residential corridor

There are several locations where properties have been developed directly along the shore. In this section C, the main road is typically situated at about 100-150m (330-500ft.) from the shoreline. The area between the shore and the main road holds several houses, typically organised in one or two parallel rows along a secondary road. A small dune separates the houses from the beach, enabling home owners to walk directly from their property onto the beach. The width of the beach and dunes, measured from the shoreline to the parcel line of the adjoining properties varies between 15-50m (50-160ft.).

The beach houses are elevated by concrete or wooden piles. Typically the shore side properties are larger than the houses on the northern side of the main road. In this cross section the northern side of the main road can be either developed or undeveloped. Developments on this side of the main road mainly consist of communities that can span the entire width of the island from the main road to the bay side. Jamaica Beach is a good example of such a community. The public area in this cross section is limited to the beach and the main road's parcel. The many private properties and associated parcels bring considerable restrictions to the land barrier's footprint. This cross section is mostly representative for stretches along Galveston Island, but can sparsely be found on Bolivar Peninsula as well.

D: Wide residential corridor

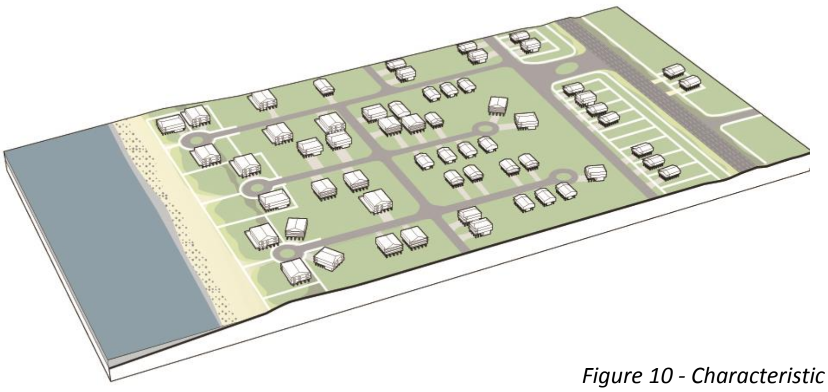


Figure 10 - Characteristic cross section D: Wide residential corridor

Cross section D is the second section which shows properties directly along the shore. Contrary to section C, the main road is located at a significant distance from the shoreline, typically between 400-600m (1300-2000ft.). The intermediate space houses small residential communities arranged along perpendicular secondary roads, which are occasionally connected to the main road. Some of these secondary roads give access to the beach. The properties vary in size; the largest are placed nearest to the shore, the smallest closer to the main road. Most properties are typical beach houses which are raised on piles. The width of the beach and dunes varies from 20 - 40 m (65-130ft.), measured from the shoreline to the outer parcel line of the local properties. This cross section is the most common form of development on Bolivar Peninsula, but also representative for several short stretches along Galveston Island.

Share of cross sections along complete stretch

The following table holds the length and the relative share of the presented cross sections for the complete project area. It shows that both land masses are a mix of cross section types. However, on Bolivar Peninsula cross section D is mostly present. Also, on Bolivar Peninsula there are no double main roads present and a large portion consist of open landscape, which is easy to design for.

On Galveston Island, the variation is much larger. Here, a large percentage consists of Galveston Seawall and open landscape. The rest of the island can best be represented with cross section C: Narrow residential corridor. There are also parts with an inland road, but these are easier to design for, as they have double roads.

	Galveston Island			Bolivar Peninsula			Total		
	km	mi	**%**	km	mi	**%**	km	mi	**%**
A1 Road in open landscape - inland	10.3	6.3	**22**	7.4	4.6	**17**	17.7	10.9	**20**
A2 Road in open landscape - shore	-	-	**0**	9.4	5.8	**22**	9.4	5.8	**10**
B Galveston Seawall	16.0	10.0	**34**	-	-	**0**	16.0	10.0	**18**
C Narrow residential corridor	11.6	7.1	**25**	8.3	5.2	**19**	19.9	12.3	**22**
D Wide residential corridor	9.0	5.6	**19**	18.0	11.2	**42**	27.0	16.8	**30**
Total	46.9	29.0	**100**	43.1	26.8	**100**	90.0	55.8	**100**

Table 4 - Amount of km/miles per cross section on both Galveston Island and Bolivar Peninsula

3.3. Selection of cross sections for technical design

Section A: Single road in open landscape will require special attention concerning its integration in the local environment. However, it does not seem to bring any large spatial restrictions on the design of the land barrier. Sections C and D prove to be more challenging, as they bring several spatial constraints for the land barriers footprint to the table. Both sections are therefore selected as design cross sections. The typical sections are made specific by selecting two actual cross sections along the Galveston Island and Bolivar Peninsula shore. Their exact locations are indicated in Appendix B. Section B, the Galveston Seawall, is not taken into account in this design as a barrier is already present here. This requires a more specific solution which is beyond the scope of this design work.

Two design cross sections

The land barrier design focuses on the two most challenging cross sections, in the previous paragraph noted as C: Narrow residential corridor and D: Wide residential corridor.

The difference can be seen in the detailed parcel map. This shows that for both occasions, the single road requires less space in terms of parcel width than the cross section with two separate roads. For the construction of the dike, it is preferred to use public parcels, as these are already government-owned and no further buy outs are needed. Therefore, if the parcel of the main road is to be used for the construction of the flood defence, the situation with a single road is more problematic. Here it is more likely the flood defence will be partly constructed on a private parcel. If this location is used, all flood defence alternatives that can be placed in the single road alternative are also feasible in the double road alternative.

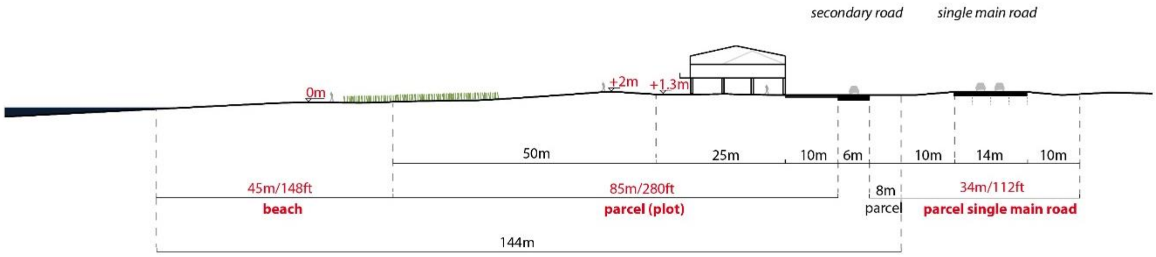


Figure 11 – Design cross section C: Narrow residential corridor – single main road

This cross section shows a single house facing the beach and sea, including its parcel, along a secondary road and a single main road. The beach is relatively wide, and the small dunes are part of the private property. Behind the main road, mainly housing and open land is present.

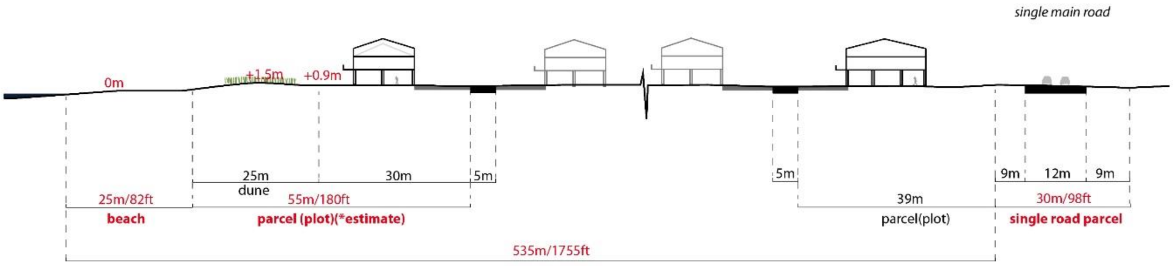


Figure 12 – Design cross section D: Wide residential corridor – single main road

The design cross section is shortened as the distance between the shoreline and the single main road is large. Both the profile of the beach and the main road is small. Interesting is the large distance between the coast and the main road. Use of public parcels will be more problematic than in the design cross section C, because the public parcel at the beach is much smaller and the main road is located at the bay-side. Behind the main road, mostly open lands are present. These cross sections will be used in the next chapter as the blueprint for flood defence system design.

4 Land barrier alternatives

This chapter discusses the different alternatives for the design of the land barrier. Because of the length of coastline along Galveston Island and Bolivar Peninsula, a land barrier placed on both land masses will have a major influence on the flood safety of the entire Galveston Bay Area.

A major challenge for the design of the land barrier is the exact location: either on the beach or at the road. The available footprint on Galveston Island and Bolivar Peninsula has already been mentioned in Chapter 3. Another challenge is the way the coastal spine is closed; e.g. the connections to higher grounds on the mainland. This leads to a barrier length that optimises flood safety for the entire region while minimizing costs and environmental interference. Two cross sections will be addressed in this chapter: Cross section C: Narrow residential corridor and Cross section D: Wide residential corridor, as discussed in section 3.3.

Extended Seawall

Earlier reports already described the land barrier conceptually (Janssen et al. 2014), most recently in the Coastal Spine report (Jonkman et al. 2015). This design showed challenges and opportunities of several structural solutions. A seawall emerged as the preferred alternative.

This was based on the requirement that its height was limited to the Galveston Seawall level of 5.2 meters (17 ft.). It would be easier to fit a concrete seawall with the same crest height, constructed as an overtopping-proof structure. In the current design it appears the height constraint of 5.2 meters is problematic, as the expected water level (including Sea Level Rise) is already above this elevation. To be able to withstand the adjusted boundary conditions as presented in chapter 2 the (covered) seawall would require to be raised significantly. This is very detrimental in terms of costs. A seawall (and other, more innovative, solutions) was evaluated during early stages of this design. However, these alternatives were considered unsuitable in terms of construction- and maintenance costs, spatial quality, flexibility and environmental impact compared to both the Coastal Dike and the Inland Dike. The main focus of the land barrier design is therefore a dike alternative. More information on the comparison with the other alternatives can be found in Appendix C.

4.1. Technical design for Cross section C: Narrow residential corridor

The first cross section that will be covered in the technical design is cross section C: Narrow residential corridor, which has the infrastructure running close to the seashore and housing mainly on the bay-side of the road. Chapter 3 showed that the cross sections are divided in public and private parcels. As the influence and cooperation of home owners still unknown, the private parcels are ideally avoided. This shows two options: either constructing the barrier on the beach parcel or the public road parcel. These options can be seen in Figure 13. Both barriers are designed for a mean overtopping volume of 50 l/s/m. Other boundary conditions and design formulae are mentioned in Chapter 2. The overtopping calculations are added in Appendix D

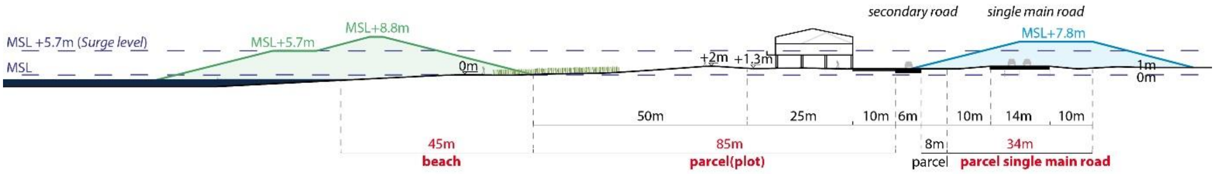


Figure 13 – C: Narrow residential corridor cross section with both possible locations: Coastal dike on the beach (green) and Enforced Highway FM3005 (blue)

	Coastal dike on beach		Enforced Highway FM3005	
Mean overtopping discharge (l/s/m)	**Crest height [m+MSL]**	**Crest height [ft.+MSL]**	**Crest height [m+MSL]**	**Crest height [ft.+MSL]**
1	11.6 m	38 ft.	10.0m	33 ft.
10	10.0 m	33 ft.	8.7m	29 ft.
50	8.8 m	29 ft.	7.8m	26 ft.
200	7.9 m	26 ft.	7.0m	23 ft.
600	7.1 m	23 ft.	6.4m	21 ft.

Table 5 – Required crest height coastal dike on beach and enforced highway FM3005

Coastal dike on the beach

The entire coastal dike is to be constructed beyond the private parcels. This dike needs a lot of material. Figure 13 shows that a dike has to be constructed with a crest height of 8.8 m (29 ft.) and a berm at the surge level of 5.7 m (19 ft.). The coastal dike brings opportunities to incorporate secondary functions or features such as dunes or integration with residential areas, although this complicates the design as well.

A very important side note is the impact on the coastal system. The barrier is built out in the Gulf of Mexico, which will most likely cause (extra) erosion and large nourishment costs to maintain. More information can be found in Chapter 5.3.

Enforced Highway FM3005

Technically the most feasible solution is the construction of the dike at the current location of Highway FM3005 across Galveston Island. The width of the road varies between 34 meters (110 ft.) and 62 meters (200 ft.). This limits the effective construction area and probably requires (parts of) private parcels to be raised, because the footprint width probably exceeds the public parcel width. A location further back from the sea means that waves are damped by the shallowness of the island. This results in a lower impacting wave on the barrier and subsequently a lower crest height is necessary. A raised main road is also a safer road during a surge event, as it will still be accessible during a storm, except for the most critical part of the storm. Therefore, safer evacuation is possible than on a road on ground level. Also, it is relatively easy and safe to construct. Downside of a barrier further inland is the fact that houses in front of the dike remain unprotected, although the presence of the barrier prevents large-scale flow towards the bay and the scour at the foundation piles that result from it.

4.2. Technical design for cross section D: Wide residential corridor

The second cross section is cross section D: wide residential corridor, where the main road runs at the bayside of the islands and most of the houses are built between the road and the sea. This cross section is predominantly featured on Bolivar Peninsula. For this cross section two barrier locations are possible: at the beach and inland. Just like for cross section C the inland alternative leaves the houses between the sea and the dike unprotected. Both options are shown in the figure below.

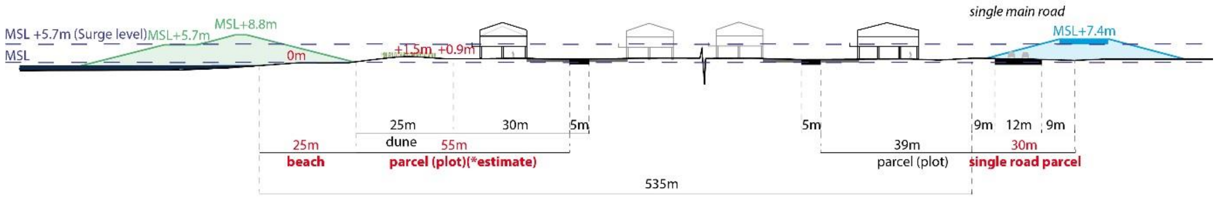


Figure 14 – D Wide residential corridor cross section with both possible locations: Coastal dike on the beach (green) and Enforced Highway SH87 (blue)

The figure shows that the distance between the sea and the road is larger in comparison to cross section C; 535 m (1750 ft.) versus 144 m (470 ft.). The shallowness the waves have to cross before reaching the barrier is even greater than for cross section C. This results in a lower design crest height. See Table 6. Refer to appendix D for the overtopping calculations. The available space for a coastal barrier is significantly smaller than for cross section C as the private parcels are closer to the shoreline.

Table 6 – Required crest height coastal dike on beach and enforced highway SH87

	Coastal dike on beach		Enforced Highway SH87	
Mean overtopping discharge (l/s/m)	**Crest height [m+MSL]**	**Crest height [ft.+MSL]**	**Crest height [m+MSL]**	**Crest height [ft.+MSL]**
1	11.6m	38 ft.	9.3m	31 ft.
10	10.0m	33 ft.	8.2m	27 ft.
50	8.8m	29 ft.	7.4m	24 ft.
200	7.9m	26 ft.	6.8m	22 ft.
600	7.1m	23 ft.	6.4m	21 ft.

Coastal dike on the beach

Just like for cross section C the entire coastal dike is to be constructed beyond the private parcels. The coastal dike protects all houses at the coast. The beach parcel is slightly smaller than for cross section C, which places the coastal barrier further seaward. This makes it more expensive. Because the coastal barrier will have to be placed further out into the sea, the impact on the coastal system will be even stronger and more material will be required.

Enforced highway SH87

Because of the small beach parcel, the option where a dike is placed at the main road will be significantly cheaper. The long distance between the sea and the dike also means that waves are smaller and a relatively low dike height is sufficient to ensure its task to protect the hinterland.

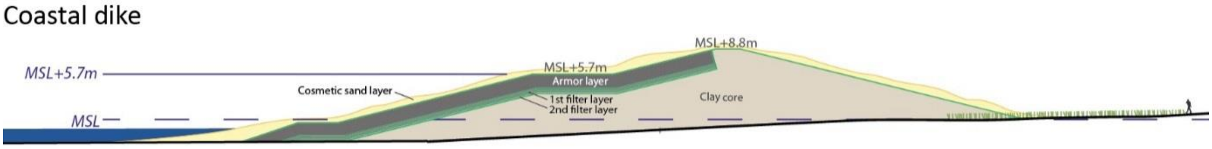
The obvious downside is the fact that the dike does not protect the houses between the beach and the road. However, nothing changes for the residents. They keep their view on the sea and they are in as much danger of flooding as they were before construction of the dike, although safe evacuation is easier. In this cross section, the difference in amount of people unprotected is higher.

4.3. Summary of alternatives and concluding remarks

In this chapter, several options for a land barrier are presented as part of the coastal spine. All of these alternatives protect the hinterland against the destructive power of hurricane induced storm surges. These are listed in the table below.

	Alternatives	
Cross section C. (Galveston Island)	Coastal barrier at 8.8m+MSL	Inland barrier FM3005 at 7.8m+MSL
Cross section D. (Bolivar Peninsula)	Coastal barrier at 8.8m+MSL	Inland barrier SH87 at 7.4m+MSL

Table 7 – Summary of alternatives (Allowed overtopping: 50 l/s/m)



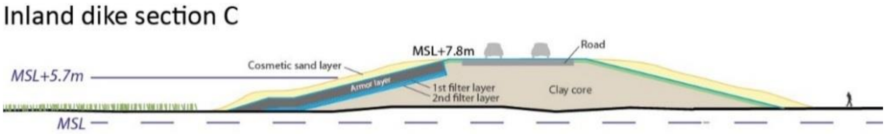


Figure 15 - cross sections of a Coastal dike and an inland dike (shown above is inland barrier FM3005)

The differences between the Coastal Barrier and the Inland barrier are summarized below:

- The coastal barrier does not interfere with private property, while an inland barrier requires local solutions to avoid the (partial) use of private parcels
- An inland barrier can be constructed with a lower crest, using less construction material, Furthermore, as the inland barrier can be constructed 'in the dry' cheaper construction materials can be applied.
- A coastal barrier interferes with the coastal system Influence into the coastal system will lead to more maintenance, either at the land barrier itself, but more likely at the ends.
- Coastal placement protects all houses on the islands, while inland barrier leaves people on the shore side vulnerable
- With placement at the road, some houses will keep their panoramic view on the beach. The road on top enables inhabitants on the other side of the barrier to enjoy the view as well.
- Placement at the road will increase the possibility of safe evacuation
- Maintenance of the inland barrier can potentially cause hindrance at the road.

The following remarks should be kept in mind:

- Most of these differences depend on the corresponding hydraulic boundary conditions are mentioned in Chapter 2. Alteration of these conditions, would lead to different dike cross sections and crest heights.
- The results as mentioned above are sensitive to the allowed overtopping. Examples of the sensitivity are shown earlier in this chapter. The allowable overtopping rate can be optimized further, although larger rates will require much larger revetments, which will be harder to include in landscape design and land use planning.
- The land barrier will have an impact on the living environment of the inhabitants. Sometimes it has to be (partially) constructed on private parcels. The owners of these private parcels probably have a high influence when it comes to decision making. The land barrier design allows for customization on a local scale, for example the construction of a seawall or movable/temporary barrier (see below). These options are not further investigated in this research.
- Additional modelling on the impact of different land barrier ends on the resulting flood risk reduction is required to enable a cost- and risk optimized land barrier design.
- Following from the calculated barrier crests, it appears that the height of Galveston Seawall is insufficient. This is based on the new hydraulic boundary conditions, which show an expected surge height above the current crest and the wish to limit the overtopping rate. This means the Seawall will also need to be raised if the same assumption would be used as for the land barrier. The design of the Seawall has not been considered in this report. More study is required to assess the existing structure and determine whether additional strengthening is required.
- Several innovations are being developed worldwide or already in place that could be interesting alternatives to the dikes. A possibility is a small dike in front of the houses with a moveable or temporary barrier on top of it. These are deployed during storms. Such solutions are probably too expensive to use on the entire island, but could be a possibility for special cases along the stretch of the coastal spine. Examples are the temporary barrier used in Central Europe or the Tsunami Barrier, which is still in development phase (Hofland et al., 2015).

5 Environmental considerations

The land barrier will have a major influence on its surroundings. The design should therefore strive to incorporate as many viewpoints and other demands and wishes in the early design. This can prevent avoidable resistance and restrictions further along the way. This chapter will shed some light on the design from other, non-technical angles. In Chapter 5.1 and 5.2, the Environmental- and Legal considerations will be mentioned, mostly based on Blackburn et al. (2015). In Chapter 5.3, Dr. J. Figlus (Texas A&M University, Galveston) will elaborate on the coastal system and the effect on the land barrier design.

5.1. Ecological considerations

When considering the environmental effects of a potential flood defence system, of which the land barrier will be a crucial piece, first the environmental effects of neglecting the risks will be clarified:

- The storm marked as the 1/100 year^{-1} storm by SSPEED Center (which differs somewhat from the 1/100 year^{-1} storm assumed in this report) will result in much higher water levels in the Galveston Bay as was experienced during Hurricane Ike in 2008. The Houston Ship Channel will experience 7.6 m (25 ft.), which is 3.7 m (12 ft.) higher than during Hurricane Ike. The economic and ecological damage of such a storm will most likely be more severe as well.
- A 7.3 m (24 ft.) surge in the HSP is estimated to result in 340 million litres (90 million gallons) of crude oil spilling in the nearby area and the Galveston Bay, one of the country's most productive fish and shellfish nurseries. For comparison, during the BP Deepwater Horizon oil-spill, around 800 million litres (210 million gallons) of crude oil spilled. (SSPEED, 2015)

As put by Blackburn et al. (2015): "*The damage caused … could easily become the worst environmental disaster in U.S. History.*"

These points illustrate the importance of a region-wide solution. The problem is that a (structural) solution in the form of a network of storm surge barriers and land barriers will also have a major impact on the ecology of the entire Galveston Bay Area. A storm surge barrier may limit the flow of salt water into the basin, disrupting the brackish environment that supports the many special forms of wildlife. Although no major influences on the marine wildlife are expected (after all, the barrier will mostly be placed on land), the impact of a potential barrier at the coast can influence the sediment transport. The type of sediment varies locally depending on the source of the barrier material. When material is brought from outside the current bay environment (sand is in short supply), this will locally change the sediment structure. As clay from the bay is mentioned as a potential source for the land barrier core, this will most likely cause no problems, although the removal of this clay will have a temporary impact on the wildlife inside the bay.

There are a few endangered species in the region. Various species of sea turtle use the beaches and bay shorelines for nesting. In the long term, this impact will probably be negligible as long as a beach is present, but the construction period could cause issues, should this include alteration of the coastline. Another endangered species is the Piping plover, which is a bird species that houses at the western- and eastern ends of both Galveston Island and Bolivar Peninsula. Altering the living environment of either the sea turtles or the piping plovers is protected under strict law, which is described in section 5.2.

The Galveston Bay is also a crucial location for migratory birds when they migrate between North America and Mexico. The birds are attracted by the Galveston Bay because of the rich feeding grounds which are essential on their route to their summer or winter habitat. Commercial fishing and shell fishing are both important economic activities in the Gulf of Mexico. The wetlands along the Gulf coast are crucial for these types of fishing as about 97% of these species need these wetlands at some moment during their life span (Colbert, 2014).

When it comes to flood protection, non-structural solutions are preferred. By using nature-based solutions and using smarter land use planning, flood risk can be reduced while minimizing environmental impact. By adjusting the land use of flood-prone areas towards more environmental uses, e.g. farming or ranching, the residual flood damage can be limited and more nature-friendly solutions for to mitigation can become feasible (Blackburn, 2015). When designing a flood defence system, the added value of a solution that minimizes the ecological impact or even enhances the local ecology (e.g. a sand engine, natural wave mitigation) should be taken into account.

5.2. Legal considerations

The land barrier will have a large impact on the appeal, the environment and the land use of the islands and around it. Because of the scale of the solution and the fact that there are no current flood defences in place, it is important to look to the legal aspects. Not only for to prevent the project from being closed down, but also because of the probable need for federal funding. These considerations have also been mentioned in Blackburn et al. (2015), on which the following points are based:

- The need of federal funding will require a closer look towards the Water Resource Development Act (WRDA), which has a central role as a guideline for the views of the federal government towards water related projects of this kind. A recent revision of this act stated its focus towards healthy, resilient ecosystems, sustainable economic growth, avoidance of unwise use of floodplains and flood-prone areas, mitigation of threats to public safety, fair treatment and the use of a watershed approach. This shows a change in the viewpoints of the federal government from purely economic towards an approach that requires the integration of social- and ecological effects. Understanding and explaining these effects will require substantial additional research.

- Another law that can have a large influence on the project is the Endangered Species Act. This law protects the living environments of species listed as ‘threatened’ or ‘endangered’. A governmental agency is not allowed to jeopardize the continued existence of a listed species. The ESA has a great influence and is able to slow or terminate water-related projects. The existence of endangered species in the area will need to be mapped and by taken into account during design.

- Many different permits are required on both state- and federal level. This must be kept in mind, as ‘federal environmental laws often reflect values not necessarily shared by local or state elected officials or by many of the residents in the area’ (Blackburn 2015). For example, this could lead to certain adjustment, needed for obtaining federal funding, being rejected for local permits. A clear statement of the choices and the underlying arguments is necessary.

- In the U.S., and Texas in particular, the individual homeowner has extensive power on the usage of their land. It must be assumed that it is impossible to force the owner of an individual private parcel to adjust or sacrifice (parts of) their land for the good of flood safety for the Galveston Bay. The solution comes in two parts: First of all, private parcels should be avoided when possible. Secondly, a clear and unambiguous message should inform the inhabitants on the necessity of the flood defence system, before the next hurricane does.

Although this is only a small sample of the complicated legislation, laws and considerations for the project, it shows a trend that could help in future decisions. The land barrier location, the desired source of funding and the overall impact on the ecology and economy of Galveston Island and Bolivar Peninsula can significantly delay the project or not, depending on whether the requirements are taken into account early on.

5.3. Coastal system

By Dr. J. Figlus. Assistant Professor, Department of Ocean Engineering, Texas A&M University, Galveston

Galveston Island and the Bolivar Peninsula separate Galveston Bay from the Gulf of Mexico (GoM) and are part of the upper Texas coast which extends from Sabine Pass at the Texas-Louisiana border to San Luis Pass at the southwestern end of Galveston Island. The Galveston Island and Bolivar Peninsula unprotected shoreline is retreating at moderate rates between 0.6 to 2.0 m/yr with some portions of Galveston's West End near the western end of the seawall retreating at rates higher than 2.0 m/yr (Pain et al., 2012; Gibeaut, 2011) whereas the portions protected by the seawall can be considered stable. Both ends of Galveston Island and the western end of the Bolivar Peninsula are accreting at rates up to 5 m/yr.

If the trend observed over the last 50 years continues, the area could see approximately 68 cm or relative sea level rise over the next 100 years. The geologic framework of the area coupled with human intervention has produced a sand-limited coastal zone, consisting only of a thin sand veneer perched on a mud substrate, with minimal new supply entering the system (Frey et al., 2014). On average, the sediment in the nearshore zone is made up of sand (84 %) and fines (16 %). The coastal sand residing in the system is very fine with a median diameter around 0.15 mm (Frey et al., 2014).

Offshore sediments outside the active surf zone along the coastline are largely mud-dominated but some limited pockets of beach quality sand exist (White et al., 1985; Siringan and Anderson, 1994; Anderson and Wellner, 2002; Finkl et al., 2004; Williams et al., 2012). Offshore beach quality sand is mainly contained within sand banks like Heald Bank (55 km offshore) or Sabine Bank (110 km offshore) with an estimated 585 million cubic meters and 1.2 billion cubic meters of material, respectively (Morton and Gibeaut, 1993). The general direction of net longshore sediment transport along most of the northern and central Texas coastline is to the southwest (Hall, 1976; Mason, 1981) but a divergent nodal zone (reversal in net direction) is present in the vicinity of the western portion of the Galveston seawall. East of this region net sediment transport is in a northeasterly direction toward the entrance of the Bolivar Roads ship channel (King, 2007; Morang, 2006), whereas west of the nodal zone net transport is directed toward the West End of Galveston Island and San Luis Pass (Frey et al., 2014). Most dramatic changes in morphology and sediment transport are experienced during extreme events such as tropical storms or hurricanes. These events redistribute sediment and often provide the only source of material to allow for barrier island transgression via roll-over mechanisms.

Things to keep in mind for the design of the land barrier:

- The structure will be located on a transgressive barrier island, parts of which are fortified (Galveston seawall) and parts of which are not (Galveston West End, Bolivar Peninsula). The design needs to be able to address potential erosion issues.
- Surface sediments are mainly fine sands but they are perched over clay substrate sometimes already found at 1m depth only (or even as outcrops on the surface). Sand and clay do not follow the same sediment transport formulations.
- The system is sediment starved, or at least limited, due to the reduced introduction of new sandy sediment into the system. That means the persisting background erosion will likely continue or increase in the future and will have to be combatted with frequent re-nourishment efforts.
- The area has one of the largest subsidence rates in the country due to extraction of oil, gas, and water and the composition of the local soil. This leads to accelerated relative sea level rise that needs to be accounted for in the design. On a local level differential settling may also cause issues that need to be addressed through adequate design considerations.
- Sand resources are limited and/or expensive, but clay material can be obtained locally at a fraction of the cost of sand.
- The continental shelf is very wide (~ 200 km) and beaches have very shallow slopes (1/30 – 1/50). During storm surge events this may lead to extended periods of high water levels due to pronounced fore-runner surges. The land barrier needs to be adequately designed to prevent piping and wash out of material resulting from landward directed seepage flow.
- The general geometry of the coast (slope, profile) should be maintained to avoid excessive increase in background erosion rates. This means a barrier on the beach would need to be accompanied by extensive nourishment efforts to provide enough space for the footprint of the barrier where necessary.

6 Land Barrier preliminary design

The main objective of this research is provide insight into the main dimensions of a land barrier, located on Galveston Island and Bolivar Peninsula, able to significantly reduce the flood risk of the region around the Galveston Bay. In Chapter 3, the land use of both Galveston Island and Bolivar Peninsula is represented by four characteristic cross sections. Two of these cross sections were labelled as the most challenging and were therefore selected for the land barrier design. Several designs for these cross sections are elaborated in Chapter 4. This chapter presents and explains the preferred design.

The choice for the preferred design is mainly based on a cost estimate (section 6.4) and the findings of the 'Land Barrier design workshop', held at Delft, the Netherlands with a variety of experts. During this workshop, the design alternatives were reviewed and compared. The findings of the workshop can be found in *Appendix C: Comparison of Alternatives.* The considerations from the workshop were combined with a cost estimate to come to the preferred design, which is presented below.

6.1. Land Barrier overview

This section shows a first look at the preferred land barrier design. This mainly concerns the location and sort of barrier. A more detailed look at the technical cross section and the landscape design can be found in sections 6.2 and 6.3 respectively. Lastly, a cost estimate is included in section 6.4.

Location

On both Galveston Island and the Bolivar Peninsula, the current location of the main road (FM3005 and SH87 respectively) is preferred over a barrier on the beach. This is based on the following arguments:

- *The parcels are public property*; this means that no buyouts are required. This is also true for a barrier at the coast, but any other location would run into major issues concerning property rights. The footprint of the barrier may be larger than the parcel width. In this case, local solutions are needed (steeper slopes or partial use of private property).
- *The hydraulic loads are lower;* because the waves break on the shallow part in front of the barrier, the barrier can be constructed lower and cheaper. This effect is stronger as the road is located further from the shore, up to a certain limit.
- *Panoramic view on the beach remains;* one of the main reasons to live on these islands is the view on the Gulf of Mexico. Contrary to the coastal barrier, some houses will keep their panoramic view on the beach. The road on top enables inhabitants on the other side of the barrier to enjoy the view as well. People can keep their direct view on the beach if they are willing to accept the risk of flooding.
- *No influence of coastal system;* A barrier location closer to the shore is more likely to influence the coastal system, which requires expensive nourishments, additional measurements and a much more expensive maintenance. An inland barrier does not have this disadvantage.
- *Robust evacuation route;* when a storm approaches, people may want to evacuate. Evacuation will become safer and will be possible for a longer time, because the road is placed on top of the barrier.

Unfortunately there are some downsides to the use of this location, the most important one being *vulnerability*. Because of the placement of the barrier at the road, the part between the road and the shore will remain unprotected. These houses would be protected if the barrier is placed at the coast. This difference is larger at Cross section D: Wide residential corridor, where a bigger number of houses are present in the flood-prone area. To illustrate the remaining vulnerability, the number of houses is estimated which remain vulnerable because of their placement at the shore side of the barrier. In Figure 16, percentages show the relative amount of houses on the protected (green) and unprotected side (red) of the road. (Source: Google maps)

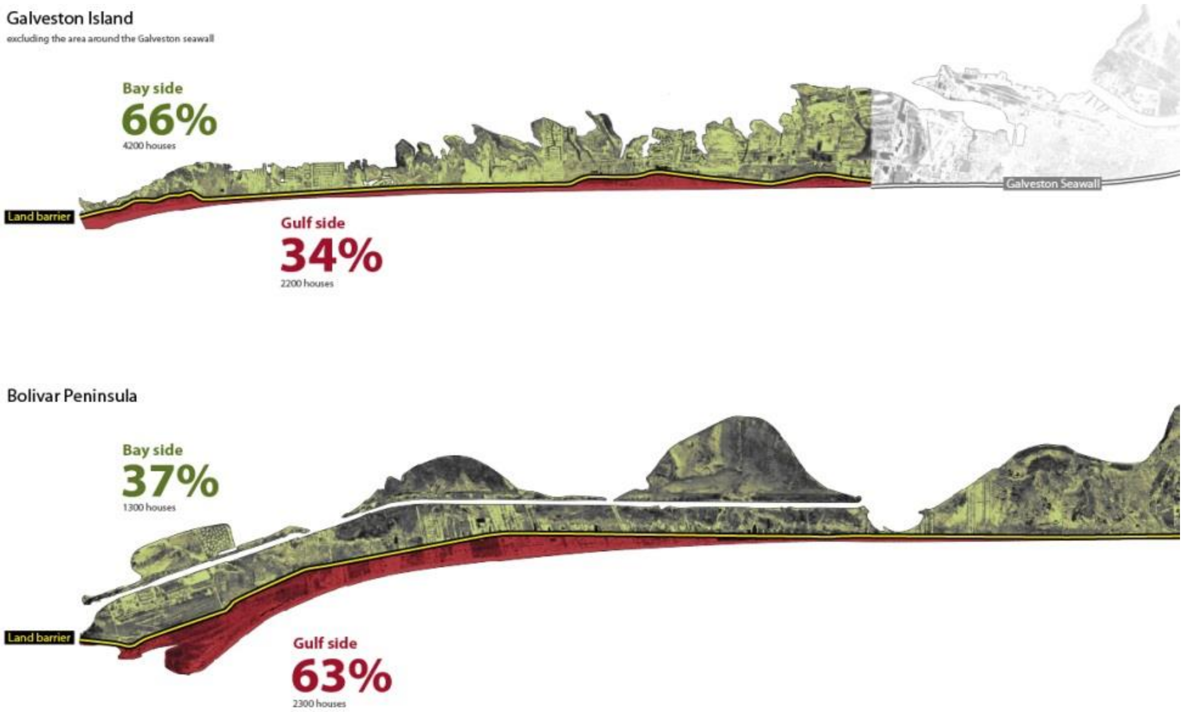


Figure 16 – Remaining vulnerability after placement of the land barrier at the road

Secondly, during *construction and maintenance* the road will have to be rerouted temporarily. However, in both cross sections the upsides of public property, cheaper construction and maintenance, partially remaining view, less influence of the coastal system and better evacuation are assumed to outweigh these issues. Selecting a preferred alternative comes down to the question whether local decision makers are willing to invest a large additional sum of money to place a barrier at the beach in order to protect all houses on the islands. The alternative is to construct the more cost-effective barrier at the road, which leaves some houses unprotected, but does not affect coastal morphology. In case the latter is chosen, a lot of money can be saved, but some issues of interference with private property need to be solved by custom-made solutions.

Barrier type

The barrier will preferably consist of a *soil-based dike with a natural cover*. The dike has a clay core, which is easily accessible and relatively cheap to obtain. To remain stable under hydraulic loading, the clay core has to be protected with a revetment. The revetment is assumed to consist of a large armor layer, because of the large waves hitting the dike. Whether this option is preferred over other forms of revetment (e.g. asphalt, concrete), requires additional research. More information on the cross section can be found in section 6.2.

Figure 17 - Layered cross section of dike-in-dune concept for the preferred design

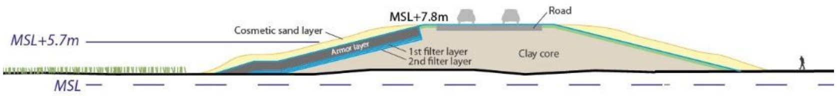
This soil-based dike has been chosen instead of a concrete and steel structure, like the Galveston Seawall. Although this kind of barrier will most likely have a smaller footprint, its non-natural appeal and sharp separation of the landscape are clear drawbacks of the seawall-like structure. The seawall has been evaluated during the land barrier design workshop and compared to the soil-based barriers. This comparison can be seen in Appendix C.

6.2. Technical design

The land barrier consists of a clay core, with a rock revetment to ensure the barrier's stability under wave attack. A cosmetic sand cover layer gives the barrier a more dune-like appearance. The barrier is designed for a maximum mean overtopping volume of 50 l/s/m. Refer to Appendix D for the overtopping calculations.

A technical cross section of the preferred land barrier design at the FM3005 (Cross section C) and at the SH87 (Cross section D) can be seen in Figure 18.

Inland dike section C



Inland dike section D

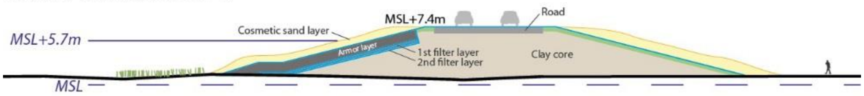


Figure 18 - Cross section for inland barrier at section C (FM3005, Galveston Island) and section D (SH87, Bolivar Peninsula)

For aesthetic reasons, it is undesirable to implement a large man-made structure with rock layer in such a natural environment. Therefore, a dike-in-dune concept is preferred where the rock layer is hidden beneath a natural-looking cover of sand and small vegetation. This layer will not have to be thick (1-2m; 3-6ft.) and does not have any flood protection responsibilities. When a (near) design storm hits, this layer will be damaged and will need repair or replacement. Because this will probably happen with a large interval, the additional costs can be considered acceptable, due to the upside of a natural look and an assumed larger acceptance from local stakeholders.

Revetment design

Using the hydraulic boundary conditions as stated in Chapter 2, some initial calculations were performed to assess the required revetment dimensions. The composition of the revetment is shown in Figure 19.

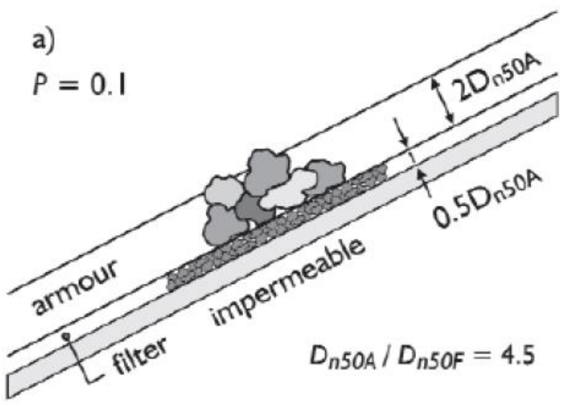


Figure 19 – Revetment composition for a clay core barrier (Rock Manual 2007 fig 5.39)

The armor layer grading is the most costly component of the revetment. It is expected a lighter revetment is required at the inland barrier, compared to a coastal barrier due to the lower incoming waves. The required armor layer grading for all barriers is calculated using the Van der Meer formulas (The Rock Manual 2007, C683-section 5.2.2.2 / CEM2002). Refer to Appendix E for an elaborated calculation. The filter layer dimensions are designed according to Rock Manual section 5.4.3.6. Underneath the 2nd filter layer a geotextile should be applied. The design of this geotextile is not included.

	Grading	Armor Thickness ($2*D_{n50A}$)	Grading	1st Filter Thickness ($0,5*D_{n50A}$)	Grading	2nd Filter Thickness ($0,5*D_{n50-F1}$)
Inland dike section C Galveston Island	300-1000kg (D_{n50A} =0,63m)	1,3m	10-60kg (D_{n50F1}=0,24m)	0,3m	45/180mm (D_{n50F2} =0,09m)	0,12m
Inland dike section D Bolivar Peninsula	300-1000kg (D_{n50A} =0,63m)	1,3m	10-60kg (D_{n50F1}=0,24m)	0,3m	45/180mm (D_{n50F2} =0,09m)	0,12m
Coastal dike [1] ***sections C + D***	*1t-3t* *(D_{n50A}=0,92m)*	*1,8m*	*60-300kg* *(D_{n50F1} =0,92m)*	*0,45m*	*90/250mm* *(D_{n50F2} =0,16m)*	*0,22m*

Table 8 – Armor layer dimensions

[1)] Revetment design for coastal dike added for comparison.

Here the following should be noted:

- An optimal composition of the revetment (armor layer, filter layer(s), geotextiles) should be designed in more detail. The paragraph concerns basic calculations, additional research is required.
- Alternative revetments have not been investigated (e.g. asphalt, custom elements). For a more detailed design it is recommended to take these into account.
- Before placing the armor elements a proper compaction of the clay core is essential in order to prevent (unequal) settlements. This compaction has not been investigated in this research.
- Design of toe construction is not included.

Due to the required thicknesses of the armor and filter layers the cosmetic sand cover needs to be at least 2m thick. This is because the grains of sand will fill the space between the rocks.

6.3. Spatial and landscape design

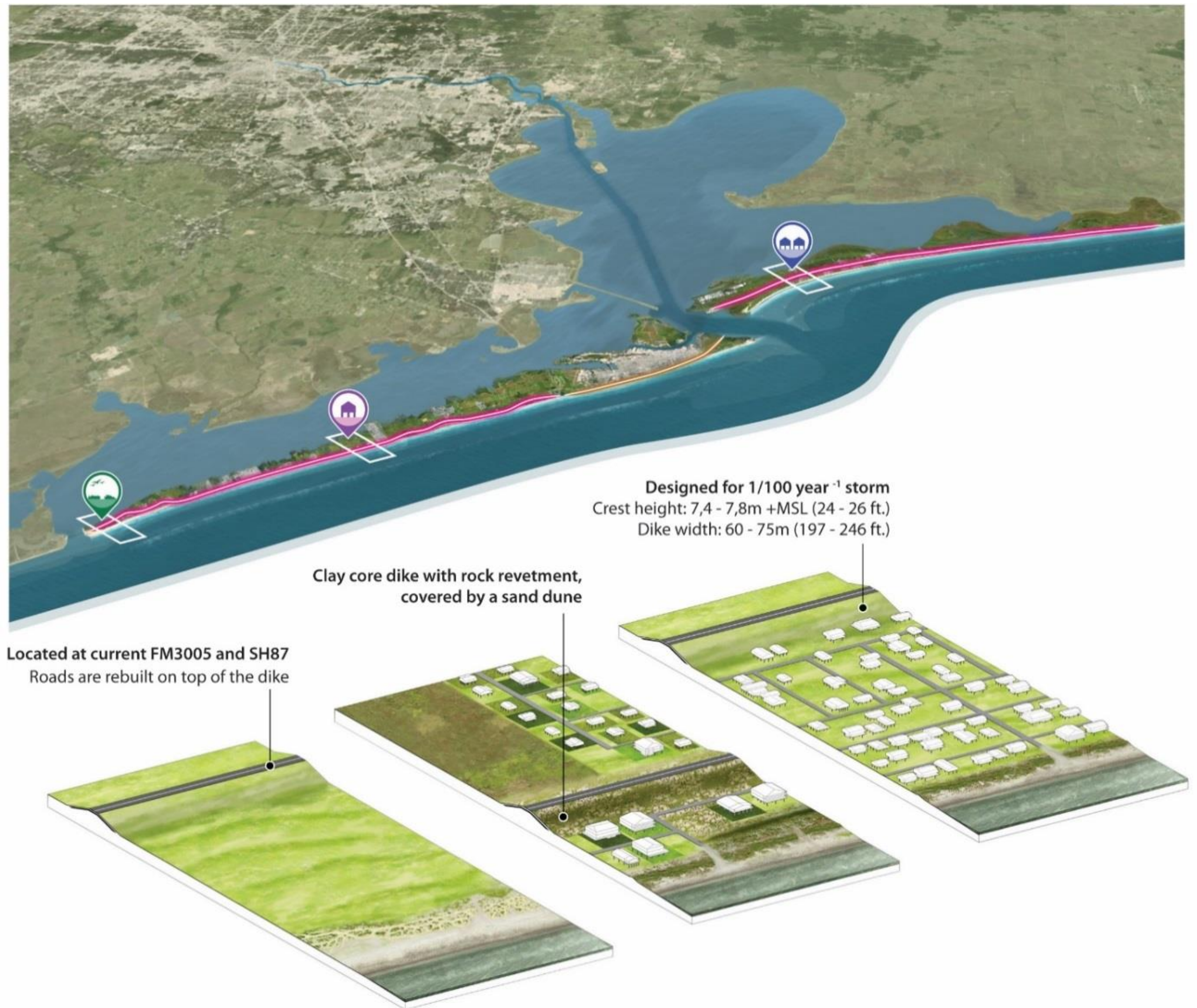


Figure 20 - Overview of the land barrier location and the corresponding land barrier cross sections

The spatial and landscape related aspects of the preferred land barrier design are discussed following the typological cross sections as explored in section 3; spatial analysis.

Land barrier in open landscape

The preferred design follows the main road's trajectory which in this case runs inland, away from the sea's shoreline. Local vegetation can fully overgrow both slopes of the barrier, it can be expected that both will fully be covered with grasses and low shrubs. As the road over the barrier will offer an impressive view over both sides of the island, the potential for creating viewpoints emerges, offering a new touristic feature to the area. These viewpoints could be combined with on and off-ramps from the road to the beach.

Land barrier along a narrow residential corridor

As the land barrier is placed behind the narrow residential corridor along the sea shoreline, the relation of the local properties with the beach and sea remains unaffected. The undeveloped plots and larger undeveloped areas in this corridor offer the potential to extend the dune landscape towards the land barrier's slopes. The barrier redefines the local spatial configuration as it walls off the sea-side properties from the main road and bay-side properties and communities. Instead the sea-side properties are now offered a view on a large dune, which is larger as some of the smaller properties. Some properties at the first rows in the bay-side residential areas will lose their sea view. Various on and off-ramps will have to be constructed to connect the local residential areas and beach to the main road.

Figure 21 - Eye level impression and cross section of inland dike

Local solutions might be needed when private properties on both sides of the barrier constrain the available footprint. Next to design optimizations such as steepening the barriers slopes, there is also the possibility for the integral redesign of the area. For example; the local properties could be raised, allowing the construction of a wider dune landscape underneath. As the properties' value is relatively large in these sections, such an undertaking could be worthwhile.

Land barrier along a wide residential corridor

The main road runs relatively far inland in these sections, and thus the land barrier's position is far away from both shorelines. The barriers sandy slopes might be overgrown with grasses and low shrubs rather than typical dune vegetation. There are not many spatial constraints along these sections, and when necessary local solutions could further limit the barriers' footprint to an acceptable size.

6.4. Cost analysis

This section presents an analysis of the constructions costs of the preferred land barrier as displayed earlier in this chapter. Costs are estimated very roughly using a material based approach. Because of the early stage of design, there is a large uncertainty in the cost estimate (±50%).

The following should be kept in mind:

- The cost estimate only accounts for the land barrier on Galveston Island and Bolivar Peninsula, from San Luis Pass to High Island. Any connections beyond these points are not included
- Road construction is not included
- Maintenance is not included
- Land buyouts are not included

The cost estimate is done for three components of the land barrier: the clay core, the revetment and the cosmetic sand cover. A distinction is made between sections A (A1 and A2 combined), C and D, as the cost unit rates differ for the revetment.

The cost estimate will assume that a dike, according to the preferred design presented in this chapter, is placed along Galveston Island and Bolivar Peninsula. This dike stretches from San Luis Pass to the Galveston Seawall and from Bolivar Roads to High Island for a total of 74 km (46 miles). For an optimized flood risk reduction, the barrier needs to be connected to higher grounds, to prevent water from running around the land barrier. This is discussed further in Chapter 6.5.

Cost unit rates are assumed as:

- Clay embankment: \$ 15/m^3
- Revetment
    - Coastal barrier: \$ 150/ton (grading 1t-3t, incl. filter layer(s), transport, placement, etc.)
    - Inland barrier: \$ 125/ton (grading 300-1000kg, incl. filter layer(s), transport, placement, etc.)
- Cosmetic sand cover (thickness 2m): \$ 50/m^3

The cost unit rates include transportation, placement etc. Initial estimates of a 300-1000kg grading from a Texas quarry amount \$20 per ton (J. Figlus, *personal communication 12-02-2016*). As this does not include any filter layers and the material is not specifically suited to coastal applications, a cost unit rate of 125 \$/ton is assumed. It is assumed the costs of a 1-3t grading are ~25% more expensive than the 300-1000kg grading (\$150/ton).

The total costs for the **inland barrier are USD 2.3 billion** (+/-50%), which is **31 M\$/km**. For comparison, the total costs of the **coastal barrier are roughly 50% higher at USD 3.5 billion** (+/-50%) or **47 M\$/km.** Refer to appendix F for the cost calculation.

The cost estimate for the inland barrier shows a large different with earlier estimates in the *Coastal Spine report*, which cost *45 M\$/km*[1], even though it was several meters lower (5.2 m/17 ft.). This difference can be explained by the costs of the reinforced concrete seawall and its foundation. Also, roadworks were included.

In further design it is advised to assess the total Life Cycle Costs (LCC). An LCC will incorporate maintenance and all other costs during its design life. This will give a much better view on the costs relative to other alternatives.

6.5. Land barrier western- and eastern ends

The main objective of the land barrier on Galveston Island and Bolivar Peninsula is to dampen the effects of a major storm on the Houston Galveston Bay Area up to a point where it can easily be repelled with local measures. This objective has to be kept in mind when determining where the exact land barrier should be located and where it should end.

Earlier modelling assumed the land barrier to be located on the entire Galveston Island and Bolivar Peninsula from the San Luis Pass in the west up to High Island in the east. However, these models showed that large portions of the natural refuges (east of Bolivar Peninsula) are heavily flooded in their role as the new route of the water from the sea to the bay. The water level in the San Luis Pass also rose significantly. The exact ending of the land barrier will have a large influence on the total project costs, as well as the overall effect of the land barrier on the flood prevention in the Bay.

More detailed analysis of the possible land barrier ends on both the western- and the eastern side can be found in Appendix G. For both the ends, two realistic options are compared and the option of not building a land barrier past the already mentioned locations. They are shown in the figure below.

[1] *The difference is larger when totals are compared: 2.3 billion USD (land barrier design) vs 4.1 billion USD (Coastal Spine report). This difference results from the Bluewater Highway, which was included in the Coastal Spine report, increasing its length to 90 km (56 miles), compared to 74 km (46 miles) for the Land Barrier design.*

Figure 22 - Potential locations for the ends of the land barrier on both the western side (left) and the eastern side (right)

Western end: The options of constructing an inland barrier will intervene with a natural reserve and will require the construction of another storm surge barrier. The land barrier along the coast (Bluewater HWY, CR-257) seems the best structural option, also because the estimated costs do not differ much from the inland option (950 M$ versus 898 M$ respectively[2]). However, the relatively large distance from the bay and the rotation of the hurricanes may lead to the choice that the additional safety of any barrier west of Galveston Island does not offset the large costs. Therefore, leaving the San Luis Pass open should be considered as an option. Obviously, additional research is required to assess the impact of different options, especially regarding morphodynamics and ecology. This research should compare the difference in flood risk reduction for the different structural options, assess the economic rate of return of these extensions and decide whether the additional investment is worth it.

Eastern end: The same choice applies for the eastern end. However, models show, combined with the rotation of the storm, that large amounts of water enter the bay through the nature reserve on the east side of Bolivar Peninsula. This strengthens the idea that a structural solution is necessary at the eastern end. As shown in Appendix G, both the inland and the coastal option have potential. The inland SH124 option is the shortest and therefore the cheapest, but runs through the nature reserve. The coastal SH87 option is more expensive, but could be used to enhance the local infrastructure and to combine with coastal solutions. However, because the shorter inland SH124 option also runs towards higher ground near Stowell, fewer measures are needed. This leads to a very significant difference in cost estimate: The 25 km SH124 inland option towards higher ground is estimated to cost around 390 M$, whereas the 50

[2] *The cost estimates are based on the costs per km from the land barrier design of Galveston Island and Bolivar Peninsula.*

km coastal SH87 option will cost roughly 1,550 M$. As this is still uncertain if it is possible and desired to use the SH87 land barrier as a coastal and infrastructural project (and because it is unlikely that these opportunities outweigh the large estimated costs difference), the inland option is preferred in the current design step.

7 Conclusions and recommendations

This report presents a conceptual design of a (potential) land barrier on Galveston Island and Bolivar Peninsula that protects the region from hurricane induced surges. The investigation has shown that different levee concepts (floodwall or coastal levee) and locations (beachfront or inland road) are possible.

To provide further information, one of the alternatives is described in this report. A preliminary design is made of a **clay-core dike protected by a rock revetment.** It is assumed in this report that the land barrier is **located at the current main roads (FM3005 and SH87)** for both Galveston Island and Bolivar Peninsula. In a preliminary evaluation, this option seems most suitable because of easier construction and maintenance, better evacuation and less impact on the coastal- and ecological system. However, the final choice of the location and construction type will depend on local stakeholder interests and decision-making.

Given the hydraulic boundary conditions, the required crest level is at **7.4-7.8 m+MSL (24-26 ft.),** based on 1/100 year^{-1} storm conditions. This is strongly influenced by the allowable overtopping rates and a conservative 100-years sea level rise estimate, both of which can be optimized further. The dike footprint is 60-75 meters wide (200-250 ft.), depending on the location and distance from the Gulf of Mexico.

According to a **dike-in-dune concept**, the revetment will be covered by a natural layer in order to give the land barrier a natural appearance. This layer is meant to be replaced after a storm hits. This option seems most suitable because of easier construction and maintenance, better evacuation and less impact on the coastal- and ecological system in comparison to alternative solutions (e.g. seawall, dune system, barrier at coast, etc.). A preliminary cost estimate shows that the construction costs of a **74 km (46 miles)** long barrier from San Luis Pass up to High Island (excluding the Galveston Seawall) are assumed to be in the order of magnitude of **2.3 billion dollars (±50%),** which is roughly **31 M$/km**. These costs do not include maintenance, road construction or the possible need to connect the land barrier to higher grounds in order to prevent the water from circumventing the land barrier.

The following can be concluded:

- *The construction of a land barrier will significantly influence the landscape and the development and land use planning of the urban areas of both Galveston Island and Bolivar Peninsula.* The safer living environment may cause increased settlement, putting stress on the local environment.

- *A barrier at the coast has also been considered and evaluated as an alternative.* It was concluded to be inferior to the proposed alternative due to a higher crest level and impact on the coastal zone. The construction costs were estimated to be 50% higher than the proposed land barrier design.

- *Constructing and maintaining a land barrier of maximum 5.2m+MSL (17ft.) will lead to large overtopping rates.* Due to the desired safety level of 1/100 year^{-1}, combined with sea level rise (±1m, 3ft.), storm surges of up to 5.7m (19ft.) with waves of up to 3.2m (10ft.) at the shoreline can be expected. Designing a barrier at these heights can be very expensive and high-maintenance.

- *The barrier at the main road will leave communities between the shore and the road unprotected.* Therefore the choice of the final location mainly depends on the demands of inhabitants, companies and local decision makers concerning residual vulnerability. The willingness to cooperate is pivotal for the choice of the location, height and structure of the land barrier.

A more detailed analysis of the impact of the land barrier on the bay is required. This shows whether the amount of overtopping is acceptable and in which way the land barrier can be connected to higher grounds. Other recommendations are stated in the following section.

7.1. Recommendations

In order to come to a final design that incorporates all viewpoints, wishes and opportunities, further exploration is needed. The following aspects require further research:

Overall design

- The design safety level (1/100 per year) is currently based on experience and common use. Further **optimization in the choice for the required level of protection is recommended.** This can be done using a cost benefit analysis. In this analysis, the additional costs of better protection and risk reduction benefits are considered and optimized. Criteria for risk to life can also be considered as a basis for design. A risk model needs to be developed to support this process.
- Several groups are working on the hydraulic boundary conditions for the upper Texas coast. Currently the design conditions differ and an agreement is required in order to make an objective assessment.
- There is insufficient knowledge on the effects of a land barrier on the coastal system. More research on the morphological effects of a nearshore land barrier is required. This can contribute to the decision for placing a land barrier near or further from the shore.
- **Additional research on the eastern- and western barrier ends is necessary**. Whether and where the barrier connects to higher grounds will greatly influence the required length and costs of the barrier, the safety provided by the barrier and total costs. More research on the additional safety of the land barrier extension towards higher ground is crucial in the search towards an economically optimized design.
- **The construction phase** has not been taken into account in this design. Especially when the land barrier is constructed along the main roads of the islands, accessibility may become problematic. This requires additional attention. Accessibility and the possibility of evacuation should be ensured at all times.
- More attention is needed for the **landscape integration.** Interaction with and collaboration from local stakeholders will be required to come to a supported solution.
- Two cross sections have been analysed. It is recommended to analyse and discuss the various solutions across the longitudinal profile. For different locations a different choice of the preferred solution can be made, even allowing for variation of the barrier location (beachfront or road) and type of solution along the alignment.
- The **Galveston Seawall** is currently constructed at 5.2 m (17 ft.). This concrete structure and the urban area it protects can withstand significant overtopping. However, design and maintenance at the current safety level – in combination with the current crest level – can become challenging and expensive. More research on the local considerations and preferences in regards to safety, risk and barrier height is recommended.

Technical design

- The nearshore conditions are computed using a one-dimensional SWAN analysis by Royal HaskoningDHV. More detailed analysis can lead to a more accurate nearshore wave height prediction.
- The current model uses uncoupled wave- and surge level data. A final assessment of hydraulic boundary conditions should use coupled data.
- The **availability of construction materials (clay, rock and sand)** is still unknown and questionable. Especially sand is mentioned as a scarce material to obtain. Whether it (and the other materials) can be obtained in these amounts and at what costs can have a major impact on the resulting cross section and should be further investigated.

- When constructing a road on top of a clay core dike, **uneven settlements** can cause damage to the road and high maintenance costs. Clay quality and settlement measures should be thoroughly investigated to prevent this.
- One should consider the opportunity of **'resilience'** into this design. When a hurricane beyond design condition hits, the land barrier can 'fail' in its task to protect the area directly behind it because of the large amounts of overflow. However, it can still provide valuable support for the total Galveston Bay-system, as long as the barrier is not destroyed. By constructing a barrier that is structurally able to withstand overtopping levels beyond the current protection level, an optimisation is possible that minimizes the barrier height and the flood risk, yet keeping surge and inflow levels in the bay at an acceptable level.
- At a more detailed level a "hydraulic optimization" of the entire coastal spine can be made to see which types of elevations (17 ft. or higher) and components (with and without storm surge barrier(s)) can be made.

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9 Appendices

Appendix A: Nearshore SWAN model

Appendix B: Design cross sections

Appendix C: Comparison of alternatives

Appendix D: Overtopping calculations

Appendix E: Revetment armor layer calculations

Appendix F: Cost calculation

Appendix G: Land Barrier ends design

Appendix A: Nearshore SWAN model

Almarshed (2015) mentions the significant wave height at the buoy location. As the water depth at the land barrier is lower than the breaking water depth, the highest possible waves will not reach the land barrier with all their energy. A one-dimensional SWAN model has been set-up to assess the propagation of a hurricane-induced wave. This is done for the 1/100 yr^{-1} conditions.

SWAN is a full-spectral wave model suitable to simulate waves in the nearshore, hence the acronym SWAN: Simulating WAves Nearshore.

The model can also calculate the wave height when propagating over the barrier islands during storm surge. The wave height gets significantly reduced; see Figure 23 and Table 9. This is useful information for designing the barriers; a barrier that is located at a distance from the shoreline benefits this wave breaking. This results in a lower design wave height and therefore a lower barrier when constructed landward

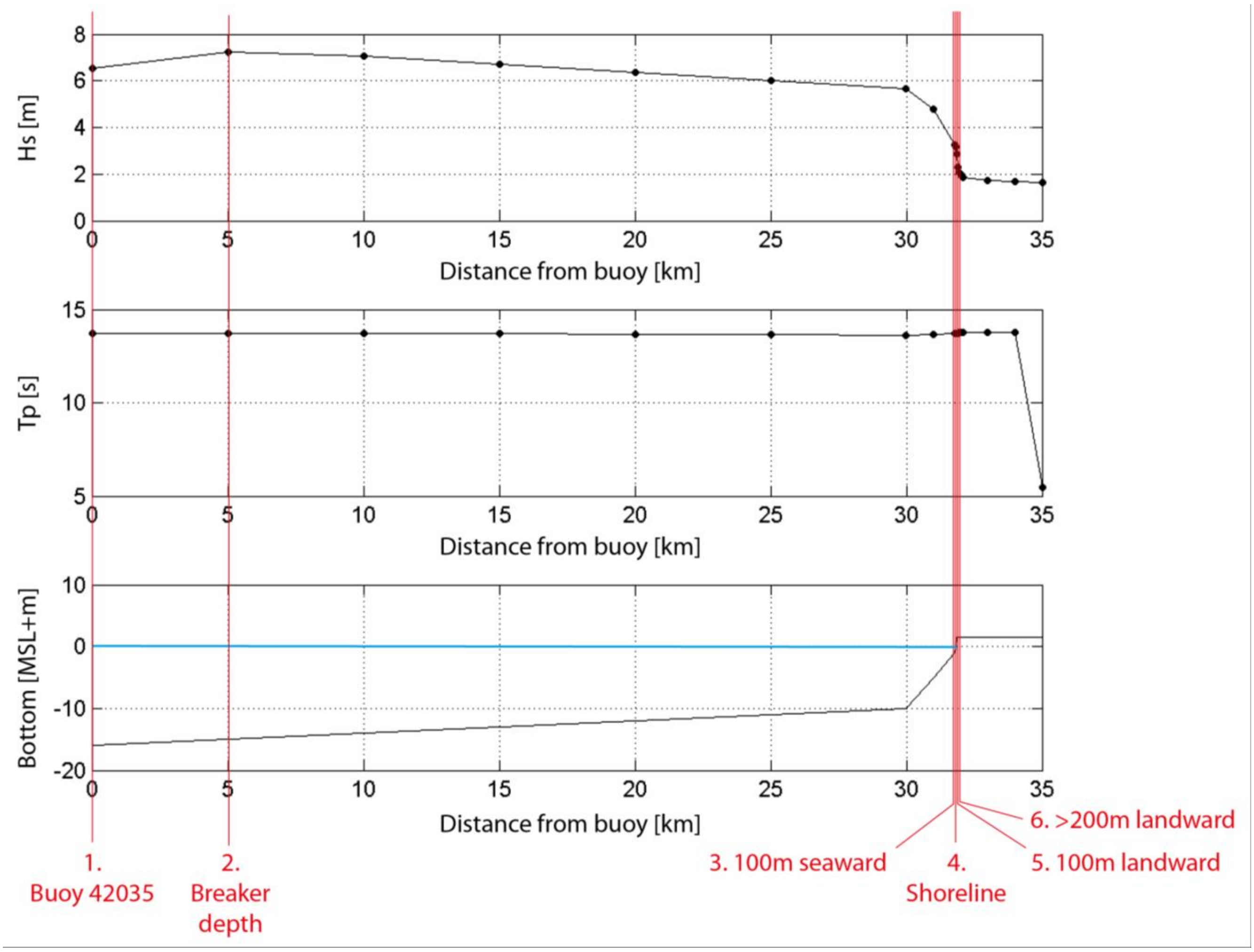


Figure 23 – SWAN results: wave transmission in the nearshore zone for the 1/100 $year^{-1}$ storm

Table 9 - SWAN results: wave conditions for several points along the along the buoy-island transect

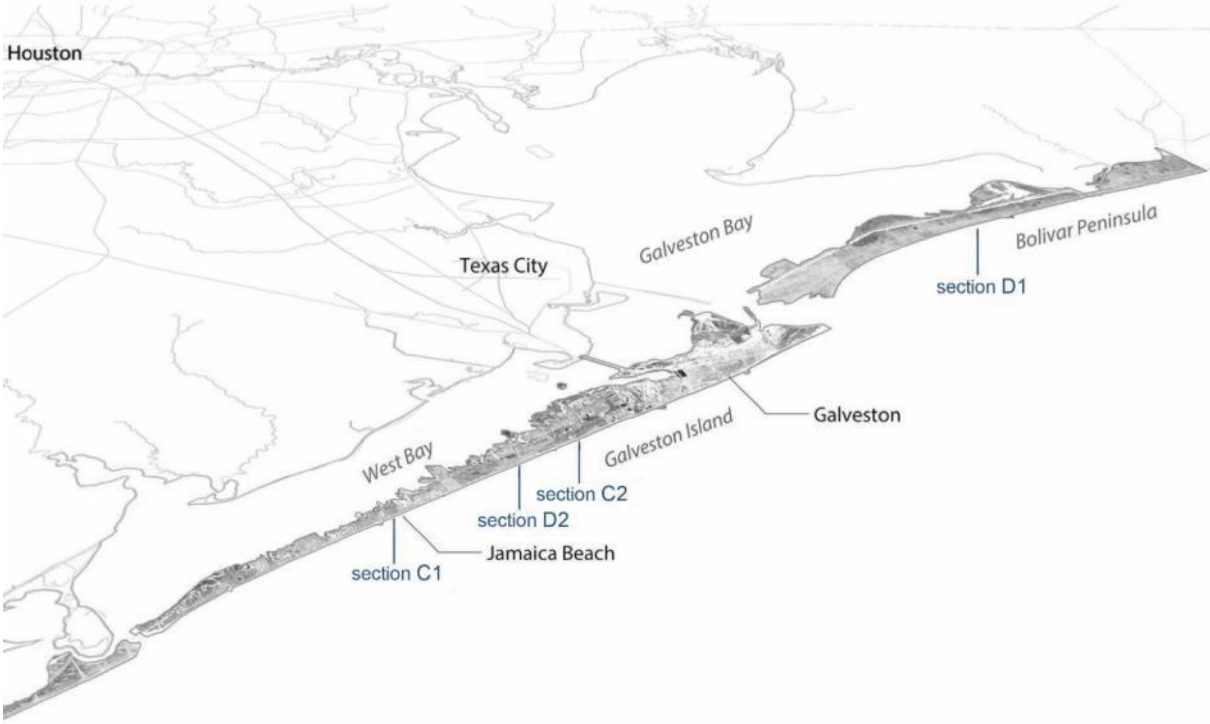
	1. Buoy (32km offshore)	2. Breaker depth (27km offshore)	3. Nearshore (100m seaward)	4. At shoreline	5. Island (100m landward)	6. Island (>200m landward)
Bottom level (m+MSL)	-16m	-15m	-1.4m	0m	+1.5m	+1.5m
Significant wave height (H_s)	6.5m	7.2m	3.4m	3.2m	2.2m	1.9m
Peak wave period (T_p)	13.7s	13.7s	13.7s	13.7s	13.7s	13.7s

The applied SWAN model has the following characteristics and limitations:

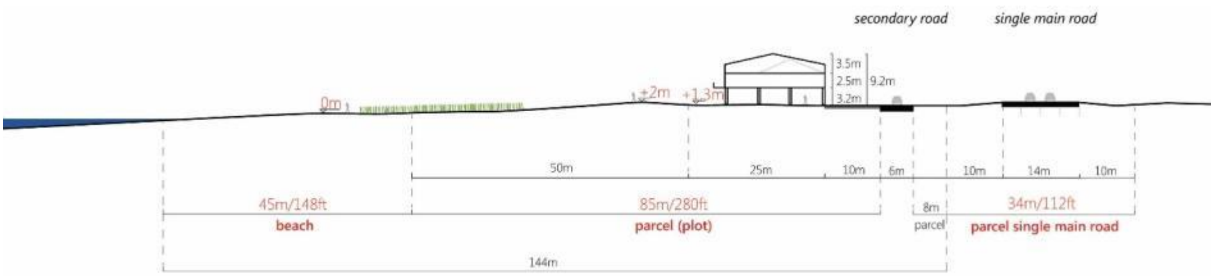
- The 1D SWAN model is 35 km long consisting of 7000 grid cells of 5 m;
- On the offshore boundary, the hurricane-induced wave is imposed as a JONSWAP spectrum with a directional spreading of 30°;
- Due to the 1D nature of the model, the wave direction is perpendicular to the shore;
- The imposed wind speed of 38 m/s is constant and uniform. This velocity corresponds to Hurricane Ike's maximum wind speed at landfall (Hope et al, 2013);
- The imposed wave has a significant wave height Hs of 6.54 m and a peak wave period Tp of 14.0 s;
- The frequency space consists of 37 frequencies ranging from a minimum frequency of 0.025 Hz and a maximum frequency of 0.8 Hz; this discrete character of the frequency space is the cause of the difference between the imposed peak wave period of 14 s and the simulated one of 13.7 s.
- The imposed surge level is MSL+5.7m and is constant and uniform;
- The bottom profile is based on the local depth at the buoy (NBDC, 2015) and Google Earth elevation data (Google, 2015);
- The wind direction is equal to the direction of wave propagation;
- The SWAN model accounts for shoaling, bed friction, depth-induced and steepness-induced breaking, non-linear wave interactions and wind growth;
- The SWAN model does not account for refraction (because it is a 1D model), (partial) reflection against steep slopes and diffraction (irrelevant in the considered situation);

Appendix B: design cross sections

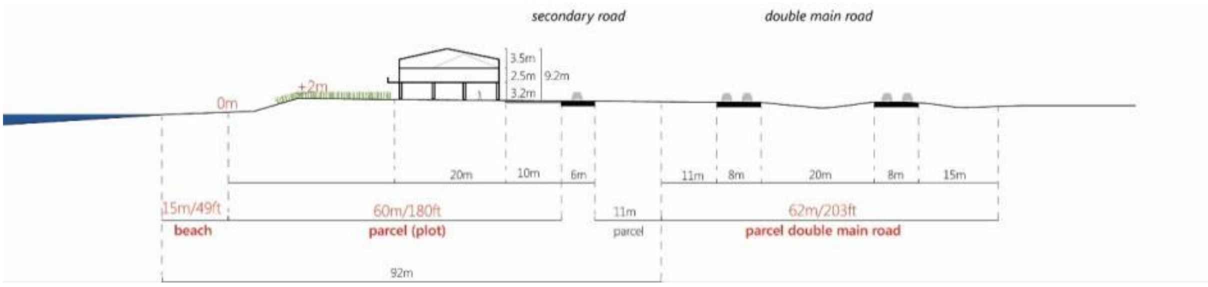
Overview of the selected design cross sections.



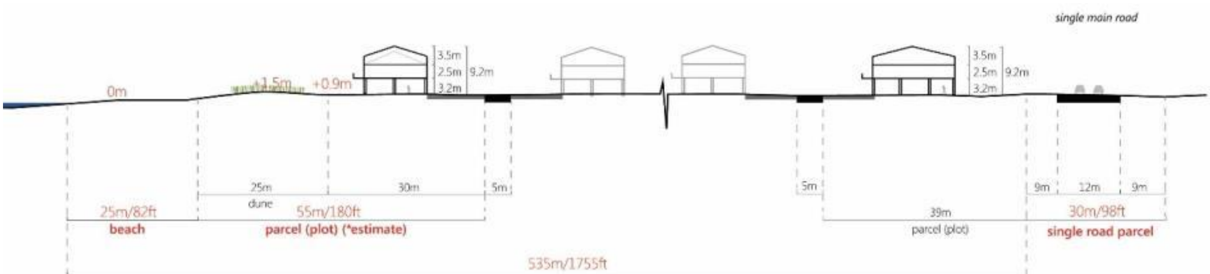
Section C1



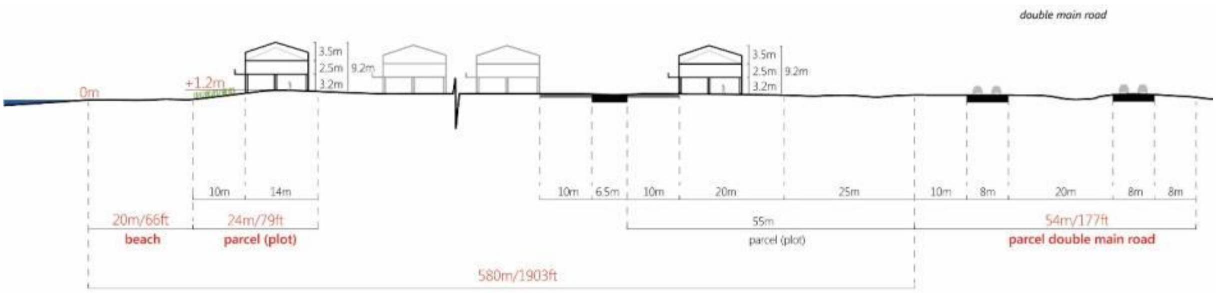
Section C2

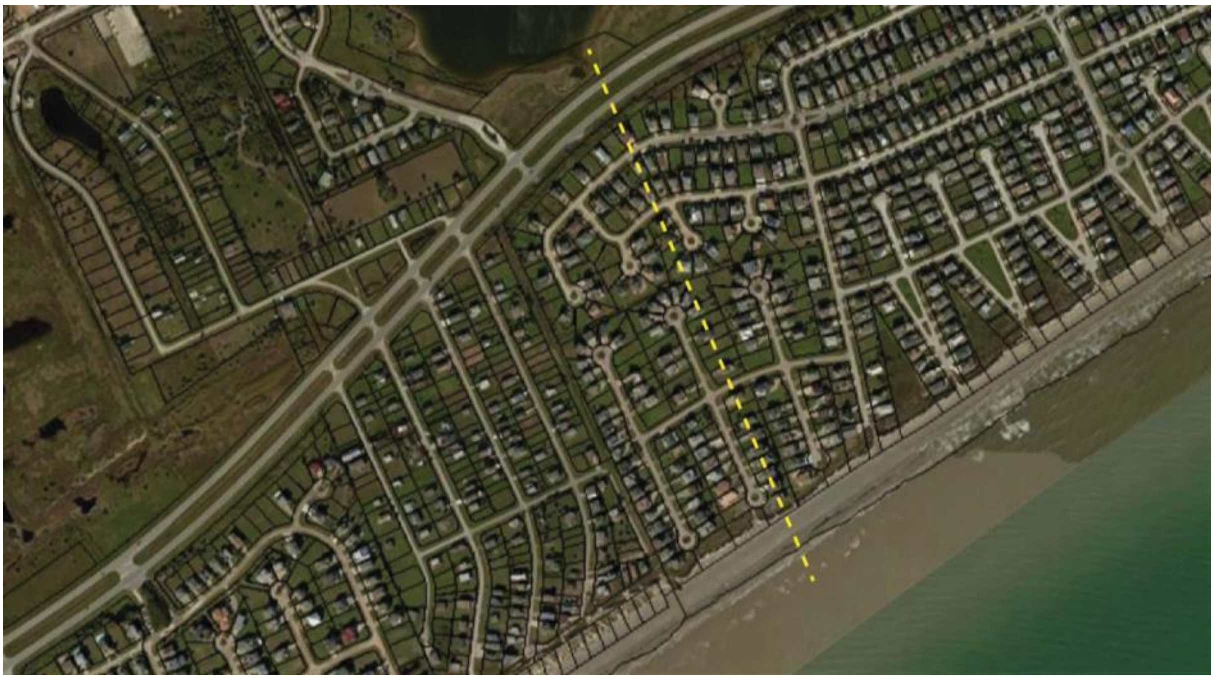


Section D1



Section D2


double main road
3.5m
2.5m
3.2m
9.2m
3.5m
2.5m
3.2m
9.2m
0m
+1.2m
10m
14m
10m
6.5m
10m
20m
25m
10m
8m
20m
8m
8m
20m/66ft
beach
24m/79ft
parcel (plot)
55m
parcel (plot)
54m/177ft
parcel double main road
580m/1903ft



Appendix C: Comparison of alternatives

This comparison is based on the workshop 'Land Barrier design' on 14th of January, 2016 at TU Delft, the Netherlands.

A large role in the preliminary land barrier design on Galveston Island and Bolivar Peninsula is reserved for a multidisciplinary review of the alternatives, which are explained earlier in this report. This review was done in the form of a workshop at TU Delft. At this workshop experts attended in the field of Hydraulic Engineering, Coastal Engineering, Coastal Modelling, Policy, Architecture and Urban Design.

The goal of the workshop was to formulate criteria to base the discussion on and review the different alternatives on those criteria. The chosen criteria on which the comparison is made are:

- Vulnerability
- Morphological impact
- Environmental/ecological impact
- Legal issues
- Spatial quality: locals
- Spatial quality: tourists
- Evacuation
- Maintenance
- Flexibility

The alternatives have deliberately not been graded on 'Public acceptance' and 'Cost'. This is chosen because the public acceptance is still mostly unknown with the reviewing group and it depends largely on the conclusions of other criteria. Cost will be quantified later and added to the comparison in order to formulate a Preferred Design. Both the cost estimate and the preferred design were not a part of the workshop.

Note: The results per criterion are summarized in a table in the form of -/0/+. These scores should only be used in comparison to each other in the respective criterion. They should not be added across the different criteria, as the criteria are not weighed.

Vulnerability

This criterion addresses the safety provided by the barrier. The main goal of the barrier is to increase the safety of the entire Galveston Bay Area and maximally decrease the damage as a result of a hurricane. In this consideration, the criterion focusses on the safety of the people, infrastructure and housing on Galveston Island and Bolivar Peninsula itself.

In the case of Cross section C: Narrow residential corridor, which is chosen on Galveston Island, this comparison shows that the provided safety of the Coastal Dike alternative is higher than the Enforced Highway FM3005 alternative, because everything behind the coast is protected. When the barrier is placed at the location of the highway however, all the housing between the highway and the coast will be affected. Because the Seawall alternative is also placed on the coast, the entire island will be protected as well, although the splashing of the waves will do more damage to anything built in front or on top of the wall. Raising the houses will also lead to every building and person being protected.

At Bolivar Peninsula (Cross section D: Wide residential corridor), much more houses are placed between the coast and the road, making the difference in vulnerability between the two locations even larger. The movable barrier will be placed on the coast as well, which improves the safety of all inhabitants.

Table 10 - Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the vulnerability of local inhabitants to flooding from hurricanes

Cross section: C – Narrow residential corridor		Cross section: D – Wide residential corridor	
Coastal dike	+	Coastal dike	+
Enforced Highway FM3005	-	Enforced Highway SH87	--
Seawall	+	Movable barrier	+
Raising houses	+	Raising houses	+

Morphological impact

The morphological impact of a measure depends on the amount of change that the alternative initiates in the coastal system. This is a large advantage to the placement at the highway, as this does not change the coastal system at all. This means that any required coastal measures can be planned and executed independent of each other. The impact on the coastal system is much larger when the barrier is placed close to the coast.

The 'raising houses'-alternative will potentially affect this system and can possibly cause erosion on the shore when the footprint of the dike underneath the raised houses comes too close to the coastline. The Coastal Dike and the Seawall will probably have a large impact on the morphology and sediment transport in the coastal system. Both alternatives will occupy the current coast and extend this into the Gulf of Mexico in order to accommodate the footprint. This extension will probably increase the erosion and will therefore require large scale coastal measures to ensure that the erosion will not reach the land barrier.

Placement of a movable barrier is most likely probable with minimal influence, although it does require the coast to be fixed and free of further erosion, which is also the case for the raising houses alternative on both cross sections.

Table 11 - Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Morphological impact'

Cross section: C – Narrow residential corridor		Cross section: D – Wide residential corridor	
Coastal dike	-	Coastal dike	-
Enforced Highway FM3005	++	Enforced Highway SH87	++
Seawall	-	Movable barrier	0
Raising houses	-/0	Raising houses	-/0

Environmental/ecological impact

Constructing a land barrier will have a large effect on the local ecological system and the situation of the entire bay. The effect of the land barrier (and other flood prevention measures) on the ecosystem in the bay, which houses large amounts of marine- and land based wildlife, requires substantial additional research. However, in this consideration only the impact on the local ecosystem is addressed, as the impact on the environment of the entire Galveston Bay is considered equal for all land barrier alternatives.

The first consideration on Galveston Island relates to the used material, where a concrete-based structure like the Seawall option would lead to a hard separation between the coastal system and the ecosystem on the island itself and the bay behind it. A soil-based barrier enables a more natural approach and could be used as a base to minimize environmental impact by developing a good landscape design. When constructed at the highway, a soil-based structure could even enhance the current exchange between wildlife at both sides of the highway by constructing ecoducts.

The current exchange between sea- and terrestrial life will be affected when changes to the beach front are made. This part of the ecosystem will only be rebuilt when a beach is placed in front of the structure. Concluding, a structure near the coast will have a larger negative impact on the environment.

Table 12- Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Ecological impact'

Cross section: C – Narrow residential corridor		**Cross section: D – Wide residential corridor**	
Coastal dike	-	Coastal dike	-
Enforced Highway FM3005	+	Enforced Highway SH87	+
Seawall	--	Movable barrier	0
Raising houses	-	Raising houses	-

Legal Issues

The land barrier has to be constructed on two land masses that currently have no place reserved for flood defences. The placement of the land barrier could therefore lead to several legal issues, which can potentially be avoided when taken into consideration at an early stage in the design. This problem mainly concerns the use of public and private space. Private parcels on Galveston Island and the Bolivar Peninsula are owned by separate inhabitants or companies, which can use that parcel as they please. Placing a land barrier on these parcels will require permission of the land owners. This complicates the construction process significantly, as a small group of owners (or even an individual owner) will be able to greatly affect the construction of the land barrier.

The legal issues will therefore be smallest when construction is concentrated at the coast, which is completely public property. The change of the coast can cause legal issues with environmental agencies, but this can be accounted for with a proper (compensation) plan.

When constructing at the highway, the issues become much clearer. As the land barrier in its current form is not able to fit inside the public parcel reserved for the main road, interference with public property is always required. This is also the case when considering that a temporary road will have to be constructed during construction. Here, local solutions can be the answer. Because the crest and the largest part of the barrier will be placed inside the public parcel, only a small and low portion of the barrier will interfere with private parcel. In most cases, this will not affect any space under the houses themselves. When the coastal parcel is used to place movable barriers, no significant legal issues are expected as well.

The largest issues are expected with the 'raising houses'-alternative, as these are mainly placed on private property. Therefore, this option requires approval and cooperation of locals. Without the support of all the affected landowners this should be viewed as a major risk.

Table 13- Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Legal issues'

Cross section: C – Narrow residential corridor		**Cross section: D – Wide residential corridor**	
Coastal dike	++	Coastal dike	++
Enforced Highway FM3005	-	Enforced Highway SH87	-
Seawall	++	Movable barrier	++
Raising houses	--	Raising houses	--

Spatial Quality: Locals

The spatial quality has a large influence on the public acceptance and the feasibility of the plan. After all, a design that actively tries to maximize the spatial quality will be accepted faster, will easier find financial support and will earlier be approved for permits. The concept of spatial quality can be divided into two forms: the spatial quality provided to locals and the spatial quality provided to tourists. This separation is needed, because these two groups can experience the same location and structure in very different ways.

This part is focused on the spatial quality for locals. As these people knowingly chose to live in a flood prone area, it is understandable that they greatly value the overall quality and beauty of their surroundings. How this compares to their appreciation of safety from flooding requires additional attention in later research. For now, it is assumed that the locals chose this location for its natural surroundings and the view on the sea/bay.

The effect of the Coastal dike remains somewhat unclear. Here, the view of the Gulf of Mexico will almost certainly disappear. The surroundings will also change with the construction of a man made dike. It is possible to cover this dike in the form of an environmentally appealing structure in line with stakeholder preferences (e.g. a dune).

The enforced highway options on both cross section show more options to increase spatial quality. For the locals that had view on the gulf (the people living on the gulf side of the road), the view remains. The people on the other side had little view on the gulf to begin with. The elevated road can be used to also enforce its function as the lifeline of the islands. In cooperation with local preferences, additional function in the form of e.g. nature, recreation, shops, and viewpoints can be added in the design plans.

The seawall option will most likely show the least potential to increase spatial quality for locals. The concrete structure will heavily interfere with the natural environment. As the beach and the accessibility of the beach is assumed to be of great value to the locals, additional measures should be taken to ensure that these remain at least the same. The addition of a beach in front of the seawall will lead to erosion, which also requires other non-natural measures to contain. Ramps are needed to ensure the accessibility of the beach by car. In short, many measures are required to ensure that the spatial quality for locals does not worsen.

The raising houses alternative is similar to the coastal dike, with the difference being that the houses will be higher and will largely keep their view on the Gulf. The movable barrier will require some change in the coastal part and regular checks and tests, which will have to be done in cooperation with locals.

Table 14- Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'spatial quality: locals'

Cross section: C – Narrow residential corridor		**Cross section: D – Wide residential corridor**	
Coastal dike	-/0	Coastal dike	-/0
Enforced Highway FM3005	+	Enforced Highway SH87	+
Seawall	-	Movable barrier	-
Raising houses	+	Raising houses	+

Spatial Quality: Tourists

This part focusses on the spatial quality for tourists. Tourists are only there (mostly on Galveston Island) for a short amount of time, are not or hardly affected by flooding and mostly need an incentive to choose this area as a vacation destination. A man made structure in the form of a dike will affect the natural appeal that could attract tourist. On the other hand, the structure can be used as a breeding/shelter place for animals or could be accompanied with viewpoints/information to enhance the experience for nature seekers. Also other additional functions can be added to improve tourism, e.g. restaurants/hotels on the crest with great view.

The coastal dune, when covered with a natural layer, will increase the spatial quality for tourists, as it does show the natural dune and they don't care about the lost view for inhabitants. However, a positive effect is only possible when a new beach is constructed. The same holds for the raising houses alternative, although a truly naturally dune is hard when the raised houses are taken into account.

The enforced highway option hardly affects the tourist experience. Because a non-natural part of the island (the highway) is used and adjusted, the incentive for tourists to come and their experience does not change. The design can however be used to add additional tourist functions.

The Seawall option will largely have a negative effect, as the concrete will change the natural appeal of the islands. Due to its location, it is hard to combine the construction with other measures to offset this effect. Lastly, the movable barrier will hardly have effect on tourist, as they will only be able to see it in special occasions.

Table 15 - Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'spatial quality: tourists'.

Cross section: C – Narrow residential corridor		Cross section: D – Wide residential corridor	
Coastal dike	+	Coastal dike	+
Enforced Highway FM3005	0	Enforced Highway SH87	0
Seawall	-	Movable barrier	0
Raising houses	0/+	Raising houses	+

Evacuation

The criterion of evacuation takes several processes into account. First of all, there is the physical action of evacuation. How does the barrier change this? Secondly, the sense of safety is also important. Because a large, expensive structure is built near the houses, the people will automatically feel safer. It also takes away their view on the threat, the water in the Gulf. This will lead to the situation where, should evacuation be necessary, people will start to evacuate later and more people will stay behind. This feeling will only grow over the years, as the confidence in the flood protection grows and the memory of flooding fades. This effect will happen for all alternatives.

However, when the barrier is built near the road, a part of the inhabitants will still be affected and the danger of the water is visible from the road, both reminding all inhabitants of Galveston Island and Bolivar Peninsula of the risk and the possible need for evacuation. An additional advantage of the enforced highway options is that the evacuation route is heightened and still accessible up to the last moment before the height of the storm.

Table 16- Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Evacuation'.

Cross section: C – Narrow residential corridor		Cross section: D – Wide residential corridor	
Coastal dike	-	Coastal dike	-
Enforced Highway FM3005	+/++	Enforced Highway SH87	+/++
Seawall	-	Movable barrier	-
Raising houses	-	Raising houses	-

Maintenance

The maintenance is an important part in the lifecycle of the flood protection, which often gets too little attention during design. A badly maintained structure will severely limit the amount of time this structure can withstand design conditions.

When it comes to maintenance, there is a great downside to coastal solutions. Because the barrier will be constructed seaward of the current coast, large amount of erosion will occur. This will require regular nourishments to maintain the wanted coast profile. This effect is the largest when using the Coastal Dike, as this reaches into the sea the most. The Seawall needs a smaller footprint, but has the added effect of the salt water on the reinforced concrete structure. The raised houses has the smallest amount of maintenance of the coastal solution, but a large portion of the maintenance need to be done on private property, which complicates the activities.

The easiest alternative, in terms of maintenance, is the enforced highway. Here, the dike is very easy accessible and the amount of required maintenance will be minimal. The movable barrier will result in small adjustments to the coastline and will also require a fixed shoreline, which means that nourishments will have to be done.

Table 17 - Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Maintenance'.

Cross section: C – Narrow residential corridor		**Cross section: D – Wide residential corridor**	
Coastal dike	--	Coastal dike	--
Enforced Highway FM3005	+	Enforced Highway SH87	+
Seawall	--	Movable barrier	-
Raising houses	--	Raising houses	--

Flexibility

The flexibility criterion compares the alternatives on their ability to adapt to future demands. If rates whether an alternative can easily be heightened or enforced.

This shows a large advantage for the Coastal Dike. As it is soil-based, which can easily be enlarged or altered, and the lack for additional functions beside natural dune, makes it a structure than can be adapted without much problems. A Seawall can also easily be accessed, but has the problem of being a reinforced concrete structure. This means that almost any adjustment in height would require an entire replacement of the concrete element. This can be avoided by designing this component with the expansion in mind. By constructing an element with a width and amount of reinforcement that exceeds the requirements, an element can possibly be added on top without overstressing the base structure in design conditions. The Raised Houses-alternative can easily be heightened as well, although it requires access to private property again.

The enforced highway will show other problems. Although the soil-based structure can easily be heightened or enforced, the road will have to be relocated during construction. Also, the location near the community will probably lead to the dike getting other function as well, besides flood protection. These additional functions will have to adjust as well. The movable barrier will show the most issues when it comes to flexibility, as probably the entire movable barrier will have to be replaced when these elements are not built to be extended.

Table 18 - Comparison of alternatives for the land barrier on Galveston Island and Bolivar Peninsula on the criterion 'Flexibility'

Cross section: C – Narrow residential corridor		**Cross section: D – Wide residential corridor**	
Coastal dike	++	Coastal dike	++
Enforced Highway FM3005	-	Enforced Highway SH87	-
Seawall	-	Movable barrier	--
Raising houses	+	Raising houses	+

Comparison of alternatives

Above, the alternatives are rated based on these nine criteria. This rating can aid to make a final decision. However, because there are many other aspects to the design and many criteria intertwine, these criteria cannot be added. On the other side, the criteria do quickly show the strong- and weak points of the alternatives. When this is combined with a cost estimate, it should be possible to point an alternative that can be presented as the preferred alternative for this stage of design. This analysis also shows that many different aspects still need additional research, in order to be able to make a better quantifiable choice in the future.

Cross section C: Narrow residential corridor

Table 19 - Comparison of alternatives on all chosen criteria for cross section C: Narrow residential corridor

	Vulnerability	Morphological impact	Environmental impact	Legal issues	Spatial Quality: Local	Spatial Quality: Tourists	Evacuation	Maintenance	Flexibility
Coastal Dike	+	-	-	++	-/0	+	-	--	++
Enforced Highway FM3005	-	++	+	-	+	0	+/++	+	-
Seawall	+	-	--	++	-	-	-	--	-
Raising Houses	+	0/-	-	--	+	0/+	-	--	+

When cross section C: Narrow residential corridor (Galveston Island) is concerned, it shows that the Coastal Dike will probably be the easiest option to get permission, funding and the easiest to construct. The strong points include vulnerability (all people protected), legal issues (no private property), flexibility and the appeal to tourists. These are strong points that can easily persuade the (local) governments. However, the weak points can really be decisive in the long run. Especially morphological impact and maintenance will be large problems, which will leave a great mark on the projects costs over its entire life. Combined with weak position on evacuation and the blocked view for people living near the Gulf, other option may be preferred.

The Seawall option has hardly any advantages over the Coastal Dike, apart from its smaller footprint and resulting smaller morphological impact. The concrete structure, which will impact the environment, and subsequently tourism, will therefore need a clear cost benefit to be chosen over the other alternatives. It can be considered in special cases, e.g. in front of beach resorts as a form of special protection.

The ‘ Raising Houses’-alternative shows potential over the Coastal Dike, as it tries to minimize the weak points while keeping its strong points. However, it does add the need of constant informing of- and approval from local landowners. At this point in design, this is seen as a major factor. If future research shows that most landowners would approve of such collaboration, this can certainly be seen as a way to maximize the safety of everybody on the island without affecting the coastal system too much.

The Enforced Highway FM3005 shows potential in totally different fields compared to the Coastal Dike. Although it does not protect the people at gulf-side of the road, it shows large potential by improving the Highway FM3005 into a real lifeline of the island. This increases the options on evacuation and connecting the ecology on both sides of the road, while also showing potential additional value in the form of local uses of the dike itself (enhancing tourism). But the biggest upside remains the fact that is has no effect on the coastal system whatsoever. Compared to the Coastal Dike, it does show more issues concerning the use of private lands near the road and any reconstruction would require the road to be relocated. However, based on the comments stated in this section, the Enforced Highway FM3005 would be preferred over the Coastal Dike, not accounting for any difference in costs.

Cross section D: Wide residential corridor

Table 20 - Comparison of alternatives on all chosen criteria for cross section D: Wide residential corridor

	Vulnerability	Morphological impact	Environmental impact	Legal issues	Spatial Quality: Local	Spatial Quality: Tourists	Evacuation	Maintenance	Flexibility
Coastal Dike	+	-	-	++	-/0	+	-	--	++
Enforced Highway SH87	--	++	+	-	+	0	+/++	+	-
Movable barrier	+	-	0	++	-	0	-	-	--
Raising Houses	+	0/-	-	--	+	+	-	--	+

The cross section D, which is mostly present on Bolivar Island, follows mainly the same considerations. One difference is the larger amount of people living between the Gulf coast and the road. This will mean that the difference in local safety provided by the flood defence is even bigger. On the other side, because the road is placed more inland, the crest height at the road (and subsequently costs and impact) will decrease more. Also, slightly less legal issues are expected with the Enforced Highway SH87, because the bay-side of the road is mostly uninhabited.

Because the difference in vulnerability is higher than was the case at cross section C, it can be expected that homeowners will easier accept solutions near the coast, even if it blocks the view or uses their private property. Whether this shift actually occurs, is subject of later research. Here also the option of the movable barrier can be interesting. Although it has the lack of flexibility and a conditional safety (only safe if it moves/is constructed in time), the strong points of providing safety with minimal impact on the surroundings can lead to people preferring this option at certain locations.

Because the topography and infrastructure of cross section D demands an even tougher choice between two of the most conflicting criteria (vulnerability versus morphological impact), more information on mostly costs and local preference is required to choose the preferred design.

This can eventually lead to a fragmented set of solutions of pieces of land barrier where people are willing, or not, to pay more or allow construction activities on their private land. This could make the Coastal Dike (or Raising Houses, Movable Barrier) the preferred option, where other stretches lean towards the Enforced Highway SH87 based on easier construction, evacuation and less morphological and environmental impact. However, because of the limited knowledge of the local preferences and because of the early stage of design, the comments stated above will be added to the cost estimate to come up with a single preferred design.

Appendix D: Overtopping calculations

Appendix D1 - overtopping coastal barrier section C+D

Ref. Rock Manual section 5.1.1.3 - pages506 - 510 (TAW2002a method)

Special units: $l := \frac{m^3}{1000}$ $g := 9.81 \frac{m}{s \cdot s}$

Crest $:= \begin{pmatrix} 11.6 \\ 10.8 \\ 9.9 \\ 8.8 \\ 7.9 \\ 7.1 \end{pmatrix} m$

Input:

Inclination of run-up slope	$\cot\alpha := 4$	Crest elevation:	
Still water level:	$swl := 5.7 \cdot m$	Crest width:	$C_w := 0.0 \cdot m$
Spectral wave height:	$H_{mo} := 3.4 \cdot m$	Berm/toe width:	$B_B := 10 \cdot m$
Wave period, Tm-1,0 :	$T_m := 12.3 sec$	Berm lower slope:	$\cot\beta := 4$
Roughness coefficients (for rock):	$\gamma_f := 0.55$	Berm top level (mCD):	$blevel := 5.7 \cdot m$

TAW formula coefficients: For overtopping: For smooth (impermeable) slopes For wave runup:

$A_{ov} := 0.067$ $C_{ov} := 0.20$ $B_{ru} := 4.30$

$B_{ov} := 4.30$ $D_{ov} := 2.30$ $C_{ru} := 1.60$

Calculation:

Wave steepness: $s_m := \frac{2 \cdot \pi \cdot H_{mo}}{g \cdot T_m^2} = 0.014$

Slope gradient: $\tan\alpha := \frac{1}{\cot\alpha}$

Irribarren number: $\xi_m := \frac{\tan\alpha}{\sqrt{s_m}} = 2.084$

Berm reduction factor γ_b: $L_B := (1 \cdot H_{mo} \cdot \cot\alpha) + B_B + (1 \cdot H_{mo} \cdot \cot\beta) = 37.2 m$

$k_B := \frac{B_B}{L_B} = 0.269$

$h_b := swl - blevel = 0 m$

$R_{u2\%} := H_{mo} \cdot \gamma_f \cdot \left(B_{ru} - \frac{C_{ru}}{\xi_m^{0.5}} \right) = 5.968 m$ RM 5.9

$x := if(blevel < swl, 2 \cdot H_{mo}, R_{u2\%}) = 5.968 m$

$k_h := 0.5 - 0.5 \cdot \cos\left(\pi \cdot \frac{h_b}{x} \right) = 0$

$\gamma_b := 1 - k_B \cdot (1 - k_h) = 0.731$ AND with $0.6 < \gamma_b < 1$!!

$\gamma_b := if(\gamma_b < 0.6, 0.6, if(\gamma_b > 1, 1, \gamma_b))$ $\gamma_b = 0.731$

$\gamma_b \cdot \xi_m = 1.524$

If $\gamma_b \cdot \xi_m < 2$ AND $\xi_m < 5$ => **Use RM equation 5.32**

If $\gamma_b \cdot \xi_m > 2$ AND $\xi_m < 5$ => **Use RM equation 5.33**

If $\xi_m > 7$ => **Use RM equation 5.34 (shallow foreshores)**

Roughness coefficient, γ_f:

Lower limit: $\gamma_b \cdot \xi_m < 2$ => roughness coefficient as above

Upper limit: $\gamma_b \cdot \xi_m > 10$ => roughness coefficient = 1

$$\gamma_f := \text{if}\left[\gamma_b \cdot \xi_m < 2, \gamma_f, \text{if}\left[\gamma_b \cdot \xi_m > 10, 1, \left[\frac{(\gamma_b \cdot \xi_m - 2)}{10 - 2}\right] \cdot (1 - \gamma_f) + \gamma_f\right]\right]$$

Crest freeboard:

$$R_c := \text{Crest} - \text{swl} = \begin{pmatrix} 5.9 \\ 5.1 \\ 4.2 \\ 3.1 \\ 2.2 \end{pmatrix} m$$

Overtopping following RM equation 5.32 for $\gamma_b \cdot \xi_m < 2$ AND $\xi_m < 5$:

$$q_1 := \left(g \cdot H_{mo}^{\ 3}\right)^{0.5} \cdot \frac{A_{ov}}{\tan\alpha^{0.5}} \cdot \gamma_b \cdot \xi_m \cdot \exp\left(\frac{1}{\xi_m \cdot \gamma_b \cdot \gamma_f} \cdot -B_{ov} \cdot \frac{R_c}{H_{mo}}\right) \qquad q_1 = \begin{pmatrix} 5.444 \times 10^{-4} \\ 1.821 \times 10^{-3} \\ 7.082 \times 10^{-3} \\ 0.037 \end{pmatrix} \frac{m^2}{s}$$

Overtopping following RM equation 5.33 for $\gamma_b \cdot \xi_m > 2$ AND $\xi_m < 5$:

$$q_2 := \left(g \cdot H_{mo}^{\ 3}\right)^{0.5} \cdot C_{ov} \cdot \exp\left(\frac{1}{\gamma_f} \cdot -D_{ov} \cdot \frac{R_c}{H_{mo}}\right) \qquad q_2 = \begin{pmatrix} 2.77 \times 10^{-3} \\ 7.411 \times 10^{-3} \\ 0.022 \\ 0.087 \end{pmatrix} \frac{m^2}{s}$$

Overtopping following RM equation 5.34 for $\xi_m > 7$:

$$q_3 := \left(g \cdot H_{mo}^{\ 3}\right)^{0.5} \cdot 0.21 \cdot \exp\left[\frac{1}{\gamma_f} \cdot \frac{-R_c}{H_{mo} \cdot (0.33 + 0.022 \cdot \xi_m)}\right] \qquad q_3 = \begin{pmatrix} 9.322 \times 10^{-4} \\ 2.91 \times 10^{-3} \\ 0.01 \\ 0.05 \end{pmatrix} \frac{m^2}{s}$$

If 5< $\xi_m < 7$ AND $\gamma_b \cdot \xi_m < 2$ => INTERPOLATE between results for equati

$$q_4 := \left[\frac{(\xi_m - 5)}{7 - 5}\right] \cdot (q_3 - q_1) + q_1 \qquad q_4 = \begin{pmatrix} -2.106 \times 10^{-5} \\ 2.332 \times 10^{-4} \\ 2.141 \times 10^{-3} \\ 0.019 \\ 0.093 \\ 0.371 \end{pmatrix} \frac{m}{s}$$

If 5< ξ_m < 7 AND $\gamma_b \cdot \xi_m$ > 2 => INTERPOLATE between results for equati

$$q_5 := \left[\frac{(\xi_m - 5)}{7-5}\right] \cdot (q_3 - q_2) + q_2$$

$$q_5 = \begin{pmatrix} 5.451 \times 10^{-3} \\ 0.014 \\ 0.04 \\ 0.14 \\ 0.382 \\ 0.905 \end{pmatrix} \frac{m^2}{s}$$

HERE: $\gamma_b \cdot \xi_m = 1.524$

=> CHOOSE!

$$q := q_3 = \begin{pmatrix} 9.322 \times 10^{-4} \\ 2.91 \times 10^{-3} \\ 0.01 \\ 0.05 \\ 0.18 \\ 0.563 \end{pmatrix} \frac{m^2}{s}$$

Overtopping reduction over crest width => overtopping volume at back of crest:

$$C_r := 3.06 \cdot \exp\left(-1.5 \cdot \frac{C_w}{H_{mo}}\right) \qquad C_r = 3.06$$

$$C_r := \mathrm{if}(C_r > 1, 1, C_r) \qquad Q_{crest} := q \cdot C_r$$

$$Q_{crest} = \begin{pmatrix} 9.322 \times 10^{-4} \\ 2.91 \times 10^{-3} \\ 0.01 \\ 0.05 \\ 0.18 \\ 0.563 \end{pmatrix} \frac{m^2}{s}$$

$$Q_{crest} = \begin{pmatrix} 0.9322 \\ 2.9097 \\ 10.4709 \\ 50.0844 \\ 180.2336 \\ 562.5695 \end{pmatrix} \frac{l}{s \cdot m}$$

Ref. Rock Manual section 5.1.1.3 - pages506 - 510 (TAW2002a method)

Special units: $l := \frac{m^3}{1000}$ $g := 9.81 \frac{m}{s \cdot s}$

$$Crest := \begin{pmatrix} 10 \\ 9.4 \\ 8.7 \\ 7.8 \\ 7.0 \\ 6.4 \end{pmatrix} m$$

INPUT:

Still water level: $SWL := 5.7 \cdot m$

Spectral wave height: $H_{m0} := 2.2 \cdot m$

Wave period, Tm-1,0: $T_e := 12.3 sec$

Angle of wave attack, β: $\beta := 0 \quad deg$

Overtopping coefficients: $A_{ov} := 0.067$

$B_{ov} := 4.30$

$C_{ov} := 0.20$

$D_{ov} := 2.30$

Crest elevation:

Crest width: $C_w := 0 \cdot m$

Front slope gradient: $cot\alpha := 4$

Roughness coefficient (for rock): $\gamma_f := 0.55$

INTERMEDIATE CALCULAT

Crest freeboard: $R_c := Crest - SWL = \begin{pmatrix} 4.3 \\ 3.7 \\ 3 \\ 2.1 \end{pmatrix} m$

Wave steepness: $s_e := \frac{2 \cdot \pi \cdot H_{m0}}{g \cdot T_e^2} = 9.314 \times 10^{-3}$

Slope gradient: $tan\alpha := \frac{1}{cot\alpha}$

Irribarren number:
(breaker parameter) $\xi_e := \frac{tan\alpha}{\sqrt{s_e}} = 2.59$

Roughness coefficient, γ_f:
(rough slopes &
impermeable core)

Lower limit: $\xi_e < 2$ => roughness coefficient as above

Upper limit: $\xi_e >= 10$ => roughness coefficient = 1

$$\gamma_f := if\left[\xi_e < 2, \gamma_f, if\left[\xi_e > 10, 1, \left[\frac{(\xi_e - 2)}{10 - 2}\right] \cdot (1 - \gamma_f) + \gamma_f\right]\right]$$

$\gamma_f = 0.583$

Angular wave attack, γ_β: $\beta := if(|\beta| < 20, 0, if(|\beta| > 80, 80, |\beta|))$

$\beta = 0$

$\gamma_\beta := 1 - 0.0033\beta$

$\gamma_\beta = 1$

OVERTOPPING EQUATIONS:

Overtopping following RM equation 5.32 for $\xi_e < 2$:

$$q_1 := \left(g \cdot H_{m0}^{3}\right)^{0.5} \cdot \frac{A_{ov}}{\tan\alpha^{0.5}} \cdot \xi_e \cdot \exp\left(\frac{1}{\xi_e \cdot \gamma_\beta \cdot \gamma_f} \cdot -B_{ov} \cdot \frac{R_c}{H_{m0}}\right) \qquad q_1 = \begin{pmatrix} 0.014 \\ 0.03 \\ 0.073 \\ 0.234 \end{pmatrix} \frac{m^2}{s}$$

Overtopping following RM equation 5.33 for $\xi_e > 2$ AND $\xi_e < 5$:

$$q_2 := \left(g \cdot H_{m0}^{3}\right)^{0.5} \cdot C_{ov} \cdot \exp\left(\frac{1}{\gamma_\beta \cdot \gamma_f} \cdot -D_{ov} \cdot \frac{R_c}{H_{m0}}\right) \qquad q_2 = \begin{pmatrix} 9.182 \times 10^{-4} \\ 2.692 \times 10^{-3} \\ 9.44 \times 10^{-3} \\ 0.047 \end{pmatrix} \frac{m^2}{s}$$

Overtopping following RM equation 5.34 for $\xi_e > 7$:

$$q_3 := \left(g \cdot H_{m0}^{3}\right)^{0.5} \cdot 0.21 \cdot \exp\left[\frac{1}{\gamma_\beta \cdot \gamma_f} \cdot \frac{-R_c}{H_{m0} \cdot \left(0.33 + 0.022 \cdot \xi_e\right)}\right] \qquad q_3 = \begin{pmatrix} 3.721 \times 10^{-4} \\ 1.246 \times 10^{-3} \\ 5.102 \times 10^{-3} \\ 0.031 \end{pmatrix} \frac{m^2}{s}$$

If $5 < \xi_e < 7$ => INTERPOLATE between results for equations 5.33 & 5.34:

$$q_4 := \left[\frac{\left(\xi_e - 5\right)}{7 - 5}\right] \cdot \left(q_3 - q_2\right) + q_2 \qquad q_4 = \begin{pmatrix} 1.576 \times 10^{-3} \\ 4.434 \times 10^{-3} \\ 0.015 \\ 0.067 \\ 0.25 \\ 0.654 \end{pmatrix} \frac{m^2}{s}$$

OVERTOPPING RESULTS:

If $\xi_e < 2$ (AND $\xi_e < 5$)	=> Use RM equation 5.32
If $\xi_e > 2$ AND $\xi_e < 5$	=> Use RM equation 5.33
If $\xi_e > 7$	=> Use RM equation 5.34 (shallow foreshores)
If $\xi_e > 5$ AND $\xi_e < 7$	=> Interpolate between RM equation 5.33 and 5.34

Overtopping at front of crest (end of slope):

HERE: $\xi_e = 2.59$

$$q := \begin{cases} q_1 & \text{if } \xi_e < 2 \\ q_2 & \text{if } 2 \le \xi_e < 5 \\ q_4 & \text{if } 5 \le \xi_e < 7 \\ q_3 & \text{if } 7 \le \xi_e \end{cases} \qquad q = \begin{pmatrix} 0.918 \\ 2.692 \\ 9.44 \\ 47.385 \\ 198.812 \\ 582.834 \end{pmatrix} \cdot \frac{l}{s \cdot m}$$

Overtopping reduction over crest width => overtopping volume at back of crest:

$$C_r := 3.06 \cdot \exp\left(-1.5 \cdot \frac{C_w}{H_{m0}}\right) \qquad C_r = 3.06$$

$$C_r := \text{if}\left(C_r > 1, 1, C_r\right) \qquad Q_{crest} := q \cdot C_r$$

$$Q_{crest} = \begin{pmatrix} 9.182 \times 10^{-4} \\ 2.692 \times 10^{-3} \\ 9.44 \times 10^{-3} \\ 0.047 \\ 0.199 \\ 0.583 \end{pmatrix} \frac{m^2}{s} \qquad Q_{crest} = \begin{pmatrix} 0.9182 \\ 2.6917 \\ 9.4402 \\ 47.3846 \\ 198.8115 \\ 582.8338 \end{pmatrix} \cdot \frac{l}{s \cdot m}$$

Appendix D3 - overtopping inland barrier section D

Ref. Rock Manual section 5.1.1.3 - pages506 - 510 (TAW2002a method)

Special units: $l := \frac{m^3}{1000}$ $\qquad g := 9.81 \frac{m}{s \cdot s}$

INPUT:

Still water level: $SWL := 5.7 \cdot m$

Spectral wave height: $H_{m0} := 1.9 \cdot m$

Wave period, Tm-1,0: $T_e := 12.3 sec$

Angle of wave attack, β: $\beta := 0 \quad deg$

Overtopping coefficients:

$A_{ov} := 0.067$

$B_{ov} := 4.30$

$C_{ov} := 0.20$

$D_{ov} := 2.30$

Crest elevation: $Crest := \begin{pmatrix} 9.3 \\ 8.8 \\ 8.2 \\ 7.4 \\ 6.8 \\ 6.2 \end{pmatrix} m$

Crest width: $C_w := 0 \cdot m$

Front slope gradient: $cot\alpha := 4$

Roughness coefficient (for rock): $\gamma_f := 0.55$

INTERMEDIATE CALCULAT

Crest freeboard: $R_c := Crest - SWL = \begin{pmatrix} 3.6 \\ 3.1 \\ 2.5 \\ 1.7 \end{pmatrix} m$

Wave steepness: $s_e := \frac{2 \cdot \pi \cdot H_{m0}}{g \cdot T_e^2} = 8.044 \times 10^{-3}$

Slope gradient: $tan\alpha := \frac{1}{cot\alpha}$

Irribarren number: (breaker parameter) $\xi_e := \frac{tan\alpha}{\sqrt{s_e}} = 2.787$

Roughness coefficient, γ_f: (rough slopes & impermeable core)

Lower limit: $\xi_e < 2$ => roughness coefficient as above

Upper limit: $\xi_e >= 10$ => roughness coefficient = 1

$$\gamma_f := if\left[\xi_e < 2, \gamma_f, if\left[\xi_e > 10, 1, \left[\frac{(\xi_e - 2)}{10 - 2}\right] \cdot (1 - \gamma_f) + \gamma_f\right]\right]$$

$\gamma_f = 0.594$

Angular wave attack, γ_β: $\beta := if(|\beta| < 20, 0, if(|\beta| > 80, 80, |\beta|))$

$\beta = 0$

$\gamma_\beta := 1 - 0.0033\beta$

$\gamma_\beta = 1$

OVERTOPPING EQUATIONS:

<u>Overtopping following RM equation 5.32 for $\xi_e < 2$:</u>

$$q_1 := \left(g \cdot H_{m0}^{\ 3}\right)^{0.5} \cdot \frac{A_{ov}}{\tan\alpha^{0.5}} \cdot \xi_e \cdot \exp\left(\frac{1}{\xi_e \cdot \gamma_\beta \cdot \gamma_f} \cdot -B_{ov} \cdot \frac{R_c}{H_{m0}}\right)$$

$$q_1 = \begin{pmatrix} 0.022 \\ 0.044 \\ 0.101 \\ 0.3 \end{pmatrix} \frac{m^2}{s}$$

<u>Overtopping following RM equation 5.33 for $\xi_e > 2$ AND $\xi_e < 5$:</u>

$$q_2 := \left(g \cdot H_{m0}^{\ 3}\right)^{0.5} \cdot C_{ov} \cdot \exp\left(\frac{1}{\gamma_\beta \cdot \gamma_f} \cdot -D_{ov} \cdot \frac{R_c}{H_{m0}}\right)$$

$$q_2 = \begin{pmatrix} 1.072 \times 10^{-3} \\ 2.969 \times 10^{-3} \\ 0.01 \\ 0.051 \end{pmatrix} \frac{m^2}{s}$$

<u>Overtopping following RM equation 5.34 for $\xi_e > 7$:</u>

$$q_3 := \left(g \cdot H_{m0}^{\ 3}\right)^{0.5} \cdot 0.21 \cdot \exp\left[\frac{1}{\gamma_\beta \cdot \gamma_f} \cdot \frac{-R_c}{H_{m0} \cdot \left(0.33 + 0.022 \cdot \xi_e\right)}\right]$$

$$q_3 = \begin{pmatrix} 4.988 \times 10^{-4} \\ 1.546 \times 10^{-3} \\ 6.012 \times 10^{-3} \\ 0.037 \end{pmatrix} \frac{m^2}{s}$$

<u>**If 5< ξ_e < 7 => INTERPOLATE between results for equations 5.33 & 5.34:**</u>

$$q_4 := \left[\frac{\left(\xi_e - 5\right)}{7-5}\right] \cdot \left(q_3 - q_2\right) + q_2$$

$$q_4 = \begin{pmatrix} 1.707 \times 10^{-3} \\ 4.544 \times 10^{-3} \\ 0.015 \\ 0.068 \\ 0.21 \\ 0.633 \end{pmatrix} \frac{m^2}{s}$$

OVERTOPPING RESULTS:

If $\xi_e < 2$ (AND $\xi_e < 5$)	=> **Use RM equation 5.32**
If $\xi_e > 2$ AND $\xi_e < 5$	=> **Use RM equation 5.33**
If $\xi_e > 7$	=> **Use RM equation 5.34 (shallow foreshores)**
If $\xi_e > 5$ AND $\xi_e < 7$	=> **Interpolate between RM equation 5.33 and 5.34**

Overtopping at front of crest (end of slope):

HERE: $\xi_e = 2.787$

$$q := \begin{cases} q_1 & \text{if } \xi_e < 2 \\ q_2 & \text{if } 2 \le \xi_e < 5 \\ q_4 & \text{if } 5 \le \xi_e < 7 \\ q_3 & \text{if } 7 \le \xi_e \end{cases}$$

$$q = \begin{pmatrix} 1.072 \\ 2.969 \\ 10.08 \\ 51.422 \\ 174.548 \\ 592.497 \end{pmatrix} \cdot \frac{l}{s \cdot m}$$

Overtopping reduction over crest width => overtopping volume at back of crest:

$$C_r := 3.06 \cdot \exp\left(-1.5 \cdot \frac{C_w}{H_{m0}}\right) \qquad C_r = 3.06$$

$$C_r := \mathrm{if}\left(C_r > 1, 1, C_r\right) \qquad Q_{crest} := q \cdot C_r$$

$$Q_{crest} = \begin{pmatrix} 1.072 \times 10^{-3} \\ 2.969 \times 10^{-3} \\ 0.01 \\ 0.051 \\ 0.175 \\ 0.592 \end{pmatrix} \frac{m^2}{s} \qquad Q_{crest} = \begin{pmatrix} 1.0724 \\ 2.9695 \\ 10.0798 \\ 51.4215 \\ 174.5482 \\ 592.4969 \end{pmatrix} \cdot \frac{l}{s \cdot m}$$

Appendix E: Revetment armor layer calculations

Appendix E1 – armor layer coastal barrier section C+D

Coastal dike C & D, stability bank protection under wave attack (vdMeer)

Project:	BC4215 Texas Barrier
Standards:	The Rock Manual 2007-C683-section 5.2.2.2 / CEM2002
Date:	5-2-2016
By:	Ton van der Plas adapted by P.A.L. de Vries

Hydraulic parameters

Hs-toe	3,4	[m]
Hs0	unkown	[m]
Depth toe	5,7	[m]
Tp	13,7	[s]
Angle of wave	0,00	[°]
Number waves	2000	[-]
Tm-1,0 = Tp/1,1	12,45	[s]
Tm = Tp /1,15	11,91	[s]

Structural parameters

Slope cot(α) [1:n]	4,0	[-]
Slope$_{voorland}$ cot(β) [1:n]	20,00	[-]
Porosity P	0,10	[-]
$\rho_{r\text{-}stone}$	2650	[kg/m³]
ρ_{water}	1025	[kg/m³]

Required weight of primary armour

Damage S_d	12,00	[-]
c_{pl}	8,40	[-]
c_s	1,40	[-]

Wavespectrum parameters

Hmo = Hs Conservatief	3,40	[m]
Hm0 based upon H1/3	2,56	[m]
Htr	3,65	[m]
Hrms	2,70	[m]
Htr/Hrms	1,35	[m]
H2%/Hrms	1,73	[m]
H2%	4,67	[m]

Hydraulic parameters

Deep or shallow:	shallow water	[-]
Type of wave (Deep)	surging	[-]
Type of wave (Shallow)	surging	[-]
Wave length L_{0m}	221,58	[m]
Relative buoyancy Δ=	1,59	[-]
Surf similarity ξ_m =	2,02	[-]
Surf similarity ξs-1,0 =	2,11	[-]
Critical surf sim. ξ_{cr} =	1,90	[-]
Surf similarty ξ =	2,32	[-]

Validiteit vd Meer Deep

tan a	4,00	1,5	6	OK
N	2000	1	7500	OK
s0	0,02	0,001	0,06	OK
ξm	2,02	1	5	OK
delta	1,59	1	2,1	OK
h/Hs-toe	1,68	3	30	NOT VERIFIED
P	0,10	0,1	0,6	OK
Dn85/Dn15	1,50	1,5	2,5	OK
Sd/Sqrt(N)	0,27	0	0,3	OK
Hs/(delta Dn50)	3,11	0,5	4,5	OK
Sd	12	1	20	OK

Validiteit Vd Meer Shallow

tan a	4,00	2	4	OK
N	2000	1	2000	OK
s0	0,02	0,001	0,06	OK
ξm	2,02	1	5	OK
ξs-1,0	2,11	1,3	6,5	OK
H2%/Hs	1,37	1,2	1,4	OK
Hs0/h	0,60	0,25	1,5	OK
Dn85/Dn15	1,50	1,4	2	OK
Dn50-core/Dn50	0,00	0,00	0,3	OK
Hs/(delta Dn50)	2,28	0,5	4,5	OK
Sd	12	1	30	OK

Table 5.23 *Design values of the damage parameter, S_d, for armourstone in a double layer*

Slope (cotα)	Damage level		
	Start of damage	Intermediate damage	Failure
1.5	2	3–5	8
2	2	4–6	8
3	2	6–9	12
4	3	8–12	17
6	3	8–12	17

Van der Meer formulas

Deep water

Plunging : $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi_m^{-0.5}$$

Surging: $$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \sqrt{\cot\alpha}\, \xi_m^{P}$$

D_{n50} = 0,69 [m]
W_{50} = 865 [kg]

Gradation based upon EN13383
1000- 3000 kg

Shallow water

Plunging: $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \left(\xi_{s-1,0}\right)^{-0.5}$$

Surging: $$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \sqrt{\cot\alpha}\, \left(\xi_{s-1,0}\right)^{P}$$

D_{n50} = 0,94 [m]
W_{50} = 2208 [kg]

Gradation based upon EN13383
Applicable ---> 1000- 3000 kg

Appendix E2 – armor layer inland barrier section C

Inland levee C, stability bank protection under wave attack (vdMeer)

Project:	BC4215 Texas Barrier
Standards:	The Rock Manual 2007-C683-section 5.2.2.2 / CEM2002
Date:	5-2-2016
By:	Ton van der Plas adapted by P.A.L. de Vries

Hydraulic parameters

Hs-toe	2,2	[m]
Hs0	unkown	[m]
Depth toe	4,7	[m]
Tp	13,7	[s]
Angle of wave	0,00	[°]
Number waves	2000	[-]
Tm-1,0 = Tp/1,1	12,5	[s]
Tm = Tp /1,15	11,9	[s]

Structural parameters

Slope cot(α) [1:n]	4,0	[-]
Slopevoorland cot(β) [1:n]	500	[-]
Porosity P	0	[-]
$\rho_{r\text{-}stone}$	2650	[kg/m³]
ρ_{water}	1025	[kg/m³]

Required weight of primary armour

Damage S_d	12,00	[-]
c_{pl}	8,40	[-]
c_s	1,40	[-]

Wavespectrum parameters

Hmo = Hs Conservatief	2,20	[m]
Hm0 based upon H1/3	1,61	[m]
Htr	1,70	[m]
Hrms	1,69	[m]
Htr/Hrms	1,01	[m]
H2%/Hms	1,62	[m]
H2%	2,74	[m]

Hydraulic parameters

Deep or shallow:	shallow water	[-]
Type of wave (Deep)	surging	[-]
Type of wave (Shallow)	surging	[-]
Wave length L_{0m}	221,58	[m]
Relative buoyancy Δ=	1,59	[-]
Surf similarity ξ_m =	2,51	[-]
Surf similarity ξs-1,0 =	2,62	[-]
Critical surf sim. ξ_{cr} =	1,90	[-]
Surf similarity ξ =	2,89	[-]

Validiteit vd Meer Deep

tan a	4,00	1,5	6	OK
N	2000	1	7500	OK
s0	0,01	0,001	0,06	OK
ξm	2,51	1	5	OK
delta	1,59	1	2,1	OK
h/Hs-toe	2,14	3	30	NOT VERIFIED
P	0,10	0,1	0,6	OK
Dn85/Dn15	1,50	1,5	2,5	OK
Sd/Sqrt(N)	0,27	0	0,3	OK
Hs/(delta Dn50)	3,18	0,5	4,5	OK
Sd	12	1	20	OK

Van der Meer

Deep water

$$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \sqrt{\cot\alpha}\; \xi_m^{P}$$

Plunging : $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi_m^{-0.5}$$

Surging: 3,18

D_{n50} =	0,44	[m]
W_{50} =	220	[kg]

Gradation based upon EN13383

60 - 300 kg

Validiteit Vd Meer Shallow

tan a	4,00	2	4	OK
N	2000	1	2000	OK
s0	0,01	0,001	0,06	OK
ξm	2,51	1	5	OK
ξs-1,0	2,62	1,3	6,5	OK
H2%/Hs	1,24	1,2	1,4	OK
Hs0/h	0,47	0,25	1,5	OK
Dn85/Dn15	1,50	1,4	2	OK
Dn50-core/Dn50	0,00	0,00	0,3	OK
Hs/(delta Dn50)	2,57	0,5	4,5	OK
Sd	12	1	30	OK

Shallow water

Plunging: $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \left(\xi_{s-1,0}\right)^{-0.5}$$

Surging: $$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \sqrt{\cot\alpha}\, \left(\xi_{s-1,0}\right)^{P}$$

D_{n50} =	0,54	[m]
W_{50} =	417	[kg]

Gradation based upon EN13383

Applicable ---> 300 - 1000 kg

Table 5.23 *Design values of the damage parameter, S_d, for armourstone in a double layer*

Slope (cotα)	Damage level		
	Start of damage	Intermediate damage	Failure
1.5	2	3–5	8
2	2	4–6	8
3	2	6–9	12
4	3	8–12	17
6	3	8–12	17

Appendix E3 – armor layer inland barrier section D

Inland levee D, stability bank protection under wave attack (vdMeer)

Project: BC4215 Texas Barrier
Standards: The Rock Manual 2007-C683-section 5.2.2.2 / CEM2002
Date: 5-2-2016
By: Ton van der Plas adapted by P.A.L. de Vries

Hydraulic parameters

Hs-toe	1,9	[m]
Hs0	unkown	[m]
Depth toe	4,7	[m]
Tp	13,7	[s]
Angle of wave	0,00	[°]
Number waves	2000	[-]
Tm-1,0 = Tp/1,1	12,5	[s]
Tm = Tp /1,15	11,9	[s]

Structural parameters

Slope cot(α) [1:n]	4,0	[-]
Slopevoorland cot(β) [1:n]	500	[-]
Porosity P	0	[-]
$\rho_{r\text{-}stone}$	2650	[kg/m³]
ρ_{water}	1025	[kg/m³]

Required weight of primary armour

Damage S_d	12,00	[-]
c_{pl}	8,40	[-]
c_s	1,40	[-]

Wavespectrum parameters

Hmo = Hs Conservatief	1,90	[m]
Hm0 based upon H1/3	1,39	[m]
Htr	1,70	[m]
Hrms	1,43	[m]
Htr/Hrms	1,19	[m]
H2%/Hms	1,68	[m]
H2%	2,40	[m]

Hydraulic parameters

Deep or shallow:	shallow water	[-]
Type of wave (Deep)	surging	[-]
Type of wave (Shallow)	surging	[-]
Wave length L_{0m}	221,58	[m]
Relative buoyancy Δ=	1,59	[-]
Surf similarity ξ_m =	2,70	[-]
Surf similarity ξs-1,0 =	2,82	[-]
Critical surf sim. ξ_{cr}=	1,90	[-]
Surf similarty ξ =	3,10	[-]

Validiteit vd Meer Deep

tan a	4,00	1,5	6	OK
N	2000	1	7500	OK
s0	0,01	0,001	0,06	OK
ξm	2,70	1	5	OK
delta	1,59	1	2,1	OK
h/Hs-toe	2,47	3	30	NOT VERIFIED
P	0,10	0,1	0,6	OK
Dn85/Dn15	1,50	1,5	2,5	OK
Sd/Sqrt(N)	0,27	0	0,3	OK
Hs/(delta Dn50)	3,21	0,5	4,5	OK
Sd	12	1	20	OK

Validiteit Vd Meer Shallow

tan a	4,00	2	4	OK
N	2000	1	2000	OK
s0	0,01	0,001	0,06	OK
ξm	2,70	1	5	OK
ξs-1,0	2,82	1,3	6,5	OK
H2%/Hs	1,26	1,2	1,4	OK
Hs0/h	0,40	0,25	1,5	OK
Dn85/Dn15	1,50	1,4	2	OK
Dn50-core/Dn50	0,00	0,00	0,3	OK
Hs/(delta Dn50)	2,55	0,5	4,5	OK
Sd	12	1	30	OK

Table 5.23 *Design values of the damage parameter, S_d, for armourstone in a double layer*

Slope (cotα)	Damage level		
	Start of damage	Intermediate damage	Failure
1.5	2	3–5	8
2	2	4–6	8
3	2	6–9	12
4	3	8–12	17
6	3	8–12	17

Van der Me

$$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2}\sqrt{\cot\alpha}\;\xi_m^{P}$$

Deep water

Plunging: $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2}\xi_m^{-0.5}$$

Surging: 3,21

D_{n50} = 0,37 [m]
W_{50} = 138 [kg]

Gradation based upon EN13383
40 - 200 kg

Shallow water

Plunging: $$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2}\left(\frac{H_s}{H_{2\%}}\right)\left(\xi_{s-1,0}\right)^{-0.5}$$

Surging: $$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2}\left(\frac{H_s}{H_{2\%}}\right)\sqrt{\cot\alpha}\left(\xi_{s-1,0}\right)^{P}$$

D_{n50} = 0,47 [m]
W_{50} = 275 [kg]

Gradation based upon EN13383
Applicable ---> 300 - 1000 kg

Appendix F: Cost calculation

Quantities

Some general properties of the land barrier form the basis of the cost calculation. These are presented in the table below.

Coastal dike		**Cross section**		
		A [1]	**C**	**D**
Length	[km]	27,1	19,9	27,0
Raise	[m]	7,4	8,8	8,8
Berm level	[m]	N/A [2]	5,7	5,7
Barrier inland		**Cross section**		
		A [1]	**C**	**D**
Length	[km]	27,1	19,9	27,0
Raise	[m]	7,4	7,8	7,4
Berm level	[m]	N/A [2]	N/A [2]	N/A [2]

[1] Cross section A combines quantities for sections A1 & A2.
[2] The berm is only applied for the coastal barrier sections.

Cost estimate alternative 1: coastal barrier

	Specification	Quantity	unit	PPU	Total
01	**Clay Embankment**				
01.01	Section A	6.537.604	m3	$15,00	$98.064.060,00
01.02	Section C	7.823.884	m3	$15,00	$117.358.260,00
01.03	Section D	10.615.320	m3	$15,00	$159.229.800,00
02	**Revetment**				
02.01	Section A	1.097.406	ton	$125,00 1)	$137.175.695,31
02.02	Section C	1.777.686	ton	$150,00 1)	$266.652.924,74
02.03	Section D	2.411.936	ton	$150,00 1)	$361.790.400,40
03	**Cosmetic sand layer, thickness = 2m**				
03.01	Section A	3.632.590	m3	$50,00	$181.629.520,43
03.02	Section C	3.922.953	m3	$50,00	$196.147.651,43
03.03	Section D	5.322.600	m3	$50,00	$266.129.979,33
	Subtotal Direct Costs				*$1.784.178.291,64*
	Incomplete design	25	%	$1.784.178.291,64	$446.044.572,91
TDC	**Total Direct Construction Costs**				**$2.230.222.864,55**
	Construction site costs (barrier location)	10	%	$2.230.222.864,55	$223.022.286,45
	Overhead - Directional costs contractor	8	%	$2.453.245.151,00	$196.259.612,08
	Profit	5	%	$2.453.245.151,00	$122.662.257,55
TIC	**Total Indirect Costs**				**$541.944.156,08**
	Total Estimated Costs (TDC + TIC)				**$2.772.167.020,63**
	Unforeseen Project Risks	25	%	$2.772.167.020,63	$693.041.755,16
	Total construction costs				***$3.465.209.000,00***

1) The cost unit rate for the revetment of the coastal barrier sections (grading 1-3ton) are assumed to be 20% more expensive than for the inland barrier sections (grading 300-1000kg).

Cost estimate alternative 2: inland barrier

	Specification	Quantity	unit	PPU	Total
01	**Clay Embankment**				
01.01	Section A	6.537.604	m3	$15,00	$98.064.060,00
01.02	Section C	5.308.524	m3	$15,00	$79.627.860,00
01.03	Section D	6.513.480	m3	$15,00	$97.702.200,00
02	**Revetment**				
02.01	Section A	1.097.406	ton	$125,00 [1)]	$137.175.695,31
02.02	Section C	845.504	ton	$125,00 [1)]	$105.687.941,16
02.03	Section D	1.093.356	ton	$125,00 [1)]	$136.669.511,93
03	**Cosmetic sand layer, thickness = 2m**				
03.01	Section A	3.632.590	m3	$50,00	$181.629.520,43
03.02	Section C	2.798.754	m3	$50,00	$139.937.691,04
03.03	Section D	3.619.186	m3	$50,00	$180.959.300,80
	Subtotal Direct Costs				*$1.157.453.780,67*
	Incomplete design	25	%	$1.157.453.780,67	$289.363.445,17
TDC	**Total Direct Construction Costs**				**$1.446.817.225,84**
	Construction site costs (barrier location)	10	%	$1.446.817.225,84	$144.681.722,58
	Overhead - Directional costs contractor	8	%	$1.591.498.948,42	$127.319.915,87
	Profit	5	%	$1.591.498.948,42	$79.574.947,42
TIC	**Total Indirect Costs**				**$351.576.585,88**
	Total Estimated Costs (TDC + TIC)				**$1.798.393.811,71**
	Unforeseen Project Risks	25	%	$1.798.393.811,71	$449.598.452,93
	Total construction costs				***$2.247.992.500,00***

[1)] The cost unit rate for the revetment of the coastal barrier sections (grading 1-3ton) are assumed to be 20% more expensive than for the inland barrier sections (grading 300-1000kg).

Appendix G: Land barrier ends design

This appendix elaborates further on the design of the land barrier ends. On a very conceptual level, the different options in terms of location, height and cross section are considered.

Land barrier western end

This part of the land barrier focusses on the part starting at the most western point of Galveston Island, beginning with the San Luis Pass. In the first designs (e.g. Ike Dike) no structures were included here. The Coastal Spine Report (Jonkman et al., 2015) included a storm surge barrier at San Luis Pass, as well as a land barrier along the Bluewater Highway to the west of the San Luis Pass. In order to fully close of the bay from the sea on this side, a land barrier up to Freeport was needed, 20 km (12.5 miles) long. This solution was obviously a very expensive one, which encourages the search for another viable option.

However, directly north-west of the San Luis Pass, a national refuge is located, which complicates any construction inland. This also means that an inland shortcut of the dike would have to cross multiple waterways, which is considerably more expensive than a land barrier. The following alternatives seem feasible:

- No barrier at San Luis Pass and west of it
- Only a barrier at San Luis Pass
- Barrier at San Luis Pass and an inland barrier west of SLP
- Barrier at San Luis Pass and a land barrier up to Freetown

Figure 24 - Feasible alternatives for land barrier western end

The choice whether a barrier at San Luis Pass is needed or not should be based on the additional gained safety compared with the extra costs. As the San Luis Pass is a barrier across an inlet, the costs are relatively high compared to a land barrier. The additional safety provided by a San Luis Pass barrier is still unknown. The water will most likely circumvent the barrier by flooding the lands, which will locally increase the water velocities and therefore worsen the dangerous situation for the residents west of San Luis Pass.

When an additional barrier next to the San Luis Pass is needed, a choice has to be made whether a 20 km long land barrier or a shorter land/storm surge barrier combination through a nature reserve is preferred. As the shorter inland option will lead to additional environmental resistance, only a significant cost benefit compared to the extended land barrier could result in the inland option to be preferred. For comparison, the costs of the options are estimated conceptually.

The land barriers are evaluated at 31 Million dollar per kilometer (50 M$ per mile), based on costs per km estimates from the Land Barrier design report. The inland option would be a combination of a land barrier and a storm surge barrier, crossing the Cold Pass and Bastrop Bay, northwest of San Luis Pass. The expected costs per option can be found in Table 21.

Table 21 - Cost estimate for western land barrier end alternatives

Element	No Barrier	SLP + Inland barrier	SLP + Bluewater HWY
San Luis Pass	-	330 M$	330 M$
Land Barrier	-	403 M$ (13 km)	620 M$ (20 km)
Storm surge barrier	-	165 M$ (0.5 km)[1]	-
Total	**0 M$**	**898 M$**	**950 M$**

[1] Storm surge barrier costs are based on costs of San Luis Pass cost estimate from Coastal Spine report (Jonkman et al., 2015)

The cost comparison shows a relatively small different between the costs of a land barrier along the coast (Bluewater HWY, CR-257) and an inland barrier option (950 M$ versus 898 M$ respectively). However, because of the major environmental damage inflicted by the Inland barrier-option and the additional safety provided to the infrastructure by the Bluewater Highway option, the latter option will be preferred.

Whether the barrier along the Bluewater Highway is preferred over the option without any barrier depends on the additional safety provided by the barrier. Although the barrier doesn’t directly protect any houses, only the additional safety of the bay should offset the costs. Should the San Luis Pass stay open, large quantities of water will flow into the Galveston Bay. Detailed modelling will have to determine whether the resulting water level rise in the bay is harmful and whether the extension of the land barrier is the best way to counter this problem.

Land barrier eastern end

This part concerns the most eastern part of the Galveston Bay Region, east of Bolivar Peninsula. In earlier designs, the land barrier was located up until High Island, a locally elevated area slightly inland. The entire region east and north of High Island consists of nature reserves and marshland. Models showed that during a hurricane event, this region will be flooded entirely. The total inundation of the area, combined with the rotation of the hurricane, shows the possibility that the water still floods the bay by circumventing the land barrier through the eastern nature reserves. Modelling different storms and their consequences should lead to more understanding of this phenomenon.

When a local solution is required to prevent the water from entering the bay, there are two main solutions: The Inland option, which constructs a land barrier in the northern direction, along the State Highway 124 or the Coastal option, which constructs a land barrier along the partly eroded SH87.

Figure 25 - Feasible alternatives for the eastern land barrier end

The Inland SH124 option is shorter and runs towards higher ground, limiting the costs. However, it runs close to nature reserves, complicating the acquiring of required permits. The Coastal SH87 option is interesting as a larger project, because the construction of the flood defence can be combined with coastal solutions to stop erosion and the rebuilding of the partly destroyed SH87, improving the local infrastructure. However, it exceeds the boundaries of the Galveston Bay Area without reaching higher grounds. Cooperation with the local government of the area around Sabine Lake - which is partly located in Louisiana - is required to create additional value, which further increases the complexity of the project.

Therefore, the Inland SH124 option will be preferred over the Coastal SH87 option, with the side note that the restoration of the SH87 should be considered because of its possible additional value.

The estimated costs of a SH124 Land Barrier will be based on the cost per km estimate of the Land Barrier design report, which was expected to cost 31 M$ per km (50M$ per mile) and raised the land barrier for more than 7 meters(23 ft.). The SH124 runs for 25 kilometers (15.5 miles) before the ground elevation reached this height, near Stowell. Therefore, it will be assumed that a gradually smaller barrier is needed. The resulting cost estimate is 390 M$.

The Coastal SH87 option runs for a much longer distance, requires additional coastal measures and does not reach into higher lands. The project costs will thus be significantly higher. The costs of the additional coastal measures will be neglected in this comparison due to lack of insight on the required measures. The resulting stretch of land barrier is 50 km (31 miles), of which the entire barrier needs to be raised from nearly sea level. The estimated costs are 1,550 M$.

Concluding, the inland SH124 option is the shortest and cheapest route to higher grounds, but runs through a nature reserve. The coastal SH87 option is more expensive, but could be used to enhance the local infrastructure and can be combined with coastal solutions. It is still uncertain whether this approach on a SH87 land barrier is desired and it is unlikely that these opportunities outweigh the large estimated costs difference in comparison to the inland option. Therefore, in the current design step the inland SH124 towards Stowell is preferred, with the side note that the restoration of the SH87 should be considered because of its possible additional value.