RECONNAISSANCE LEVEL STUDIES ON A STORM SURGE BARRIER FOR FLOOD RISK REDUCTION IN THE HOUSTON-GALVESTON BAY

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The Houston - Galveston area is at significant risk from hurricane induced storm surges. This paper summarizes ongoing studies on flood risk reduction for the region. Firstly, based on a simplified probabilistic hurricane surge model , the return periods of surges within the bay have been estimated. This model framework can be used to assess the effectiveness of several risk reduction interventions. Sketch- and conceptual designs have been made of a storm surge barrier in the Bolivar Roads, that would be part of the Ike Dike coastal protection concept. Such a storm surge barrier would consist of two parts, an environmental section for flow requirements (consisting of caissons with vertical gates) and a navigation section of the barrier (consisting of a barge gate), which would allow unhindered passage of navigation during normal conditions. Future questions and challenges for flood risk reduction in the Bay are identified.

Keywords: storm surge barrier, hurricanes, probabilistic analysis, flood risk, coastal protection, flood defences

INTRODUCTION

Due to economic development and climate change induced effects such as sea-level rise, the risk of flooding is rising in coastal zone. In areas with larger bays, estuaries or coastal waterways, storm surge barriers can be constructed to temporarily close off these systems during storm surges in order to provide coastal flood protection. For example, in the Netherlands, several barriers have been constructed to protect the Southwest of the country after the catastrophic 1953 floods. As part of the upgraded hurricane protection system of New Orleans that was constructed after hurricane Katrina, several storm surge barriers have been built.

The Houston - Galveston Bay is at risk from hurricane induced storm surges as well. After Hurricane Ike in 2008 caused almost US $ 40 billion of damages, the concept of the Coastal Spine or Ike dike (herein further referred to as Ike Dike) has been proposed to reduce flood risk of the Galveston/Houston area (fig. 1) (Merrell et al., 2011; see also http://www.tamug.edu/ikedike/) The Ike Dike comprises a coastal protection system across the Galveston and Bolivar Islands together with a storm surge barrier in the Bolivar Roads. The Bolivar Roads is the deep-draft entrance channel to the Port of Houston. Such a system would reduce or prevent inflow of the hurricane surge into the bay and thus reduce flood risks.

Figure 1: Houston – Galveston region and proposed alignment of the Ike Dike.

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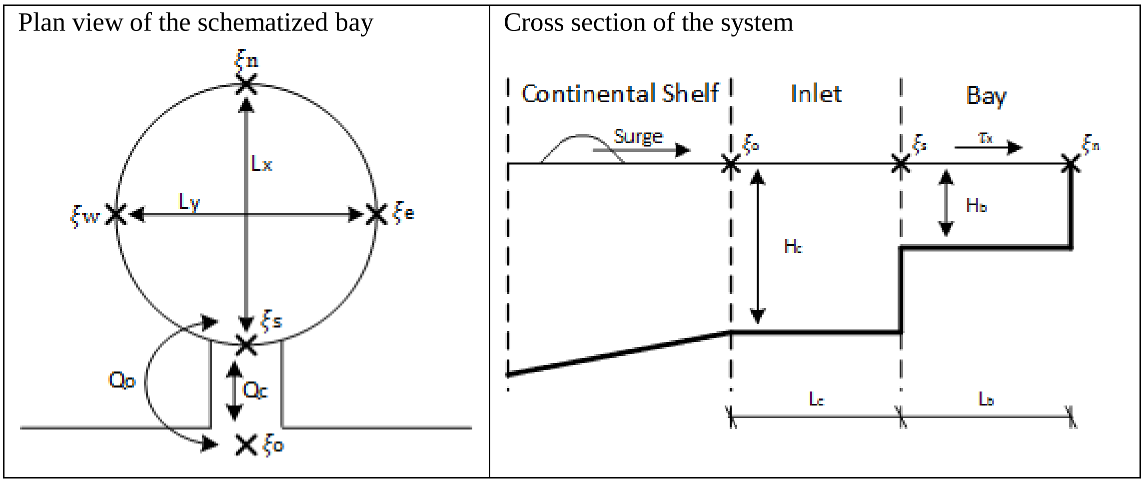
This paper gives an overview of some of the ongoing studies that are used to characterize flood risk and analyse and design the Ike Dike and other flood risk reduction solutions for the region. The main elements of the study consist of the development of a simplified probabilistic model to characterize the hydraulic effects of hurricanes on the open coast and within the Bay (section 2) and the conceptual engineering design of a storm surge barrier in the Bolivar Roads inlet (section 3). Future challenges and research questions are identified in section 4 of the paper.

PROBABILISTIC ANALYSIS OF HURRICANE SURGES

Hurricane surge

Hurricanes in the Gulf of Mexico can cause significant storm surge in the Galveston region. The surge is a result of a complex interaction between meteorological forcing and the hydrodynamic response along the coast and within the bay. The surge height depends on the storm track and intensity, but also the coastal geometry and bathymetry. For the barrier design, it is a prerequisite to have a proper insight into the surge response with a barrier in place. The key hydraulic parameter for this design is the maximum head difference (both positive and negative) when the barrier has been closed during a hurricane. This head difference determines the static loading forces at the construction and foundation.

Herein, we present a simplified probabilistic modeling approach to determine a first-order estimate of the head difference for the barrier design, see Stoeten (2013) for details. To assess the surge behavior in Galveston Bay under hurricane forcing, a simplified inlet-bay system such as studied by Lorentz (1926) and Dronkers (1964) is adopted. The mathematical model consists of a circular bay with constant depth and a constant surface area, connected to an infinitely long and straight coast by an inlet channel with negligible storage (see Figure 2). It is recognized more detailed modeling is necessary to fine tune the numbers presented herein.



Plan view of the schematized bay

Cross section of the system

Fig 2. Simplified mathematical model for determination of surge behavior in Galveston Bay with water depth H [m], water level ξ [m], length L [m] and discharge Qc [m^3/s].

Model setup

The meteorological part of the model consists of Holland's hurricane model (Holland, 1980) as modified by Blaton (Zdunkowski & Bott, 2003). This model approximates the wind velocity and surface pressure fields within the cyclostrophic region of the hurricane. Each hurricane is a random representation of four parameters: landfall location, central pressure, radius to maximum winds and forward speed of the storm. Each parameter is represented by a joint probability density function and obtained through a statistical assessment of hurricane characteristics at landfall (Chouinard et al., 1997). For a single event, the parameters are assumed invariant with time.

The hydrodynamic part of the model consists of two parts: a coastal surge model which calculates the surge level at the entrance of Galveston Bay (ξ_0 [m]) and a surge model for the water levels for four characteristic locations in the bay (ξ_s, ξ_n, ξ_e, ξ_w – subscript o refers to open coast, s to south, n to north, e to east, w to west side of the basin, see fig. 2). The coastal surge model consists of a one-dimensional approach calculating the surge along a single straight-line channel, one Radius to Maximum Winds east of the landfall location. Wave set-up at the open coast is approximated using a relation between wind and wave-setup (Resio and Westerink, 2008) and added to the calculated surge at the open coast. The calculated surge (including wave set-up) is subsequently transformed into surge at the bay inlet (ξ_0) following Bodine (1969).

The surge model of the bay consists of a coupled system of equations for both the discharge through inlet and the storage in the basin. Following Dronkers (1964) we define flow through the inlet by the momentum equation for steady one-dimensional flow governed by water level gradient in the inlet (eq. 1). When considering a bay with negligible inertia and resistance the hurricane surge propagates instantaneously into the entire bay (eq. 2). Finally, we also assume stationary conditions of the wind set-up in the bay itself along the axes of the basin L_x and L_y (eq. 3 and 4).

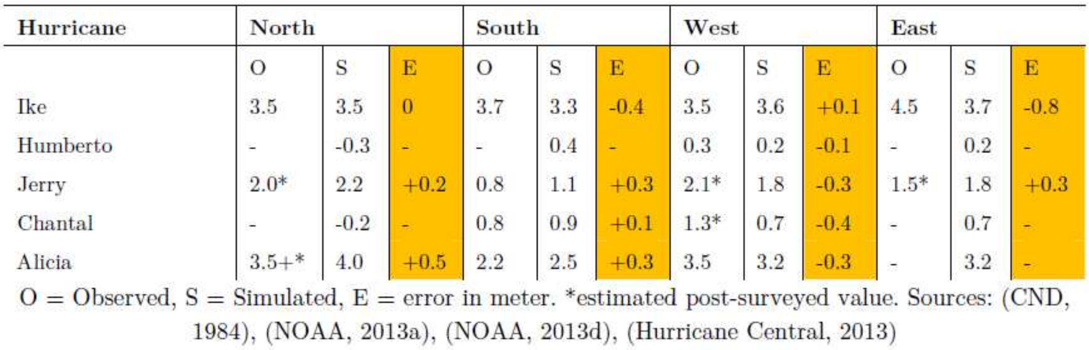
	$\frac{\xi_o - \xi_s}{L_c} = \frac{\lvert Q_c \rvert Q_c}{B_c^2 \cdot C^2 \cdot l}$	(1)
	$Q_c = A_b \frac{d}{d}$	(2)
	$\frac{\xi_s - \xi_n}{L_x} = \frac{\rho_a \cdot k \cdot W_x \lvert W}{\rho_w \cdot g \cdot (d + \xi}$	(3)
	$\frac{\xi_w - \xi_e}{L_y} = \frac{\rho_a \cdot k \cdot W_y \lvert W}{\rho \cdot g \cdot (d + \xi}$	(4)

where u is the depth averaged horizontal flow velocity along the channel axis [m/s], ξ is the surge [m], L_c is the length of the channel [m], Q_c is the flow along the channel axis [m3/s], B_c is the channel width [m], C is the Chezy coefficient [$m^{0.5}$/s], h_c is the channel depth [m], *d* is the basin depth [m], A_b is the surface area of the bay [m^2], W is the wind speed [m/s], k is the dimensionless wind friction parameter, and L_x and L_y the length of the basin in north-south and east-west direction, respectively [m].

Model validation

The surge model for Galveston Bay has been validated with five historical storms: Ike, Humberto, Jerry, Chantal and Alicia (see also Stoeten, 2013). These storms cover very different characteristics in terms of landfall location and intensity. Table 1 presents the peak water levels at different locations within Galveston Bay for 5 historical storms. It can be observed that the model matches the observed peak water levels quite well. The typical error between the observed and computed peak water levels is +/- 0.5 meter. This error magnitude is often also found with much more sophisticated models. We conclude that this idealized model provides a good first-order estimate of the expected surge levels during hurricane conditions.

Table 1: Validation of idealized hurricane surge model for Galveston Bay for different historical storms (Stoeten, 2013).



Hurricane	North			South			West			East		
	O	S	E	O	S	E	O	S	E	O	S	E
Ike	3.5	3.5	0	3.7	3.3	-0.4	3.5	3.6	+0.1	4.5	3.7	-0.8
Humberto	-	-0.3	-	-	0.4	-	0.3	0.2	-0.1	-	0.2	-
Jerry	2.0*	2.2	+0.2	0.8	1.1	+0.3	2.1*	1.8	-0.3	1.5*	1.8	+0.3
Chantal	-	-0.2	-	0.8	0.9	+0.1	1.3*	0.7	-0.4	-	0.7	-
Alicia	3.5+*	4.0	+0.5	2.2	2.5	+0.3	3.5	3.2	-0.3	-	3.2	-

O = Observed, S = Simulated, E = error in meter. *estimated post-surveyed value. Sources: (CND, 1984), (NOAA, 2013a), (NOAA, 2013d), (Hurricane Central, 2013)

The model has also been applied in a probabilistic way to define return intervals for the surge at different locations in Galveston Bay (see also Stoeten, 2013). For this purpose, model simulations have been carried out for a suite of 10^6 storms. Each storm from this suite differs in terms of the hurricane storm parameters such as central pressure, radius to max winds, forward speed and landfall location. For each model run, a value for each of these parameters has been drawn randomly from a probability density function of each parameter (pdf). The basis of these pdfs is historical information of hurricane characteristics in the Galveston region.

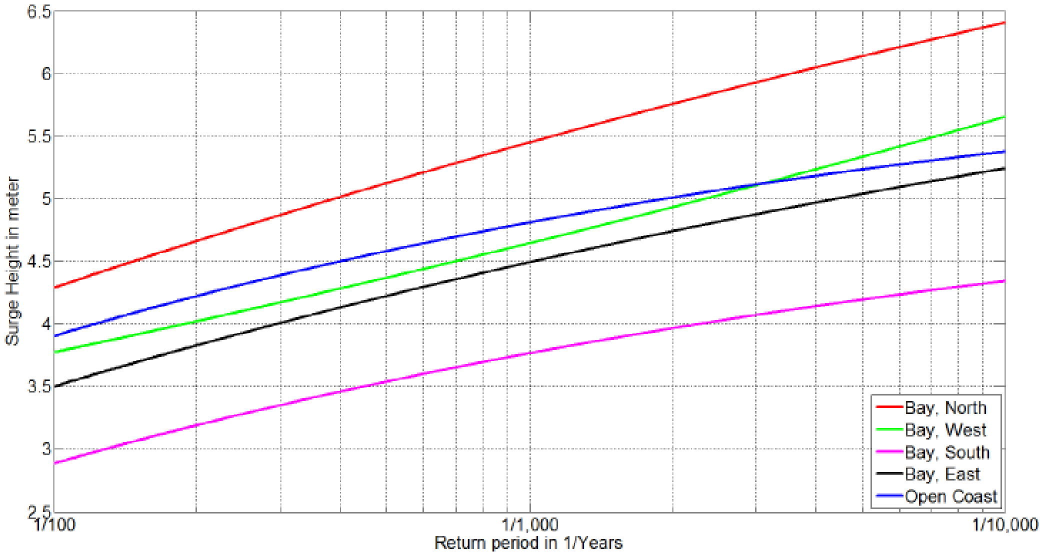


Figure 3. Return interval of surge at the open coast and within the bay based on 10^6 computations with the idealized hurricane surge model for Galveston Bay.

Figure 3 presents the surge frequency curves at different locations for Galveston Bay from the probabilistic modeling. The computed 100yr storm surge at the open coast equals 4 meters based on these simulations. This number fits well within the numbers presented in the literature which range from 3 – 4.5 meters for the 1/100yr surge level (see e.g. Bodine, 1969; Davis, 1966; NOAA, 2013). This result also confirms that the current modeling approach provides a good estimate of the surge levels during hurricanes in Galveston Bay. The model is applied in the next section to define the hydraulic head for the barrier design.

CONCEPTUAL DESIGN OF A STORM SURGE BARRIER IN THE BOLIVAR ROADS INLET

Introduction

The crossing of the Bolivar Roads has been identified as the main technical challenge of the Ike Dike system. A storm surge barrier has been proposed as an appropriate solution here. The main reason for choosing this type of structure is that it can remain open during normal conditions for the purposes of navigation and tidal exchange, but needs to be closed during a hurricane. The conceptual design for this structure is presented in this chapter.

The storm surge barrier has been divided into two parts. To facilitate navigation one wide and deep opening is required. This is called the navigation section. To preserve the ecology of the Galveston Bay sufficient tidal exchange should run through the Bolivar Roads. A large number of openings is required to allow this tidal exchange, more or less following the existing bottom profile. This part of the barrier is defined as the environmental section.

First the boundary conditions applied for the conceptual design are presented. Then, the design of the navigation and environmental sections are described. This section ends with some conclusions from the design and some topics for further research.

Hydraulic boundary conditions and other boundary conditions and requirements

For the conceptual design hydraulic calculations have been made with the model presented in the second section of this paper. Two situations for the hydraulic have been applied in the conceptual design (see also fig. 4). Different hurricane landfall locations induce a different development of the water level in front of the barrier (Gulf of Mexico side) and behind the barrier (Galveston Bay side). The landfall location 50 km west of Bolivar Roads is governing for the maximum positive head, meaning that the water level at the Gulf of Mexico is higher than the water level in the Galveston Bay.

While a hurricane that makes landfall 250 km east of the inlet results in a maximum negative head. If a negative head occurs it is recommended to open the barrier to release the head. Therefore only a small negative head of half a meter has been considered for the conceptual design.

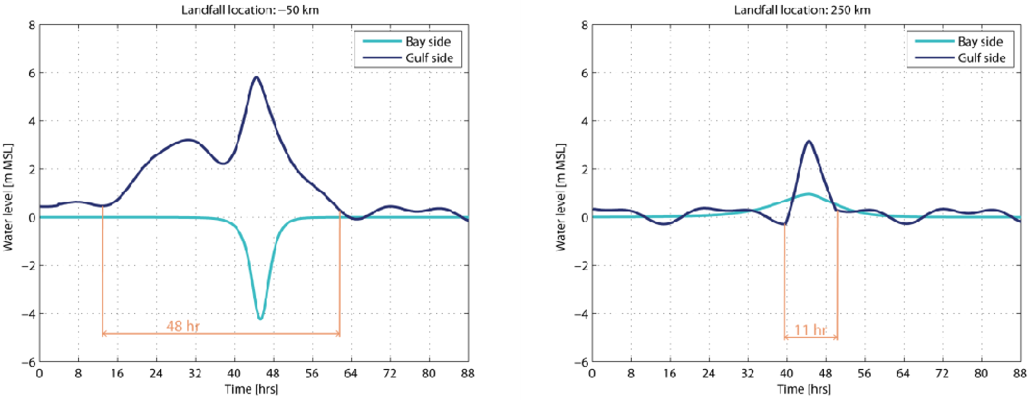


Figure 4: Maximum positive head (left) and negative head (right) for complete surge blocking barrier (MSL+6m).

Hurricanes expected to make landfall within 250km (east or west) from Bolivar Roads the barrier should be closed approximately 32 hours prior to landfall to prevent substantial inflow into the Galveston Bay (see figure 4, left). In total the barrier should remain closed for at least 48 hours, without considering closing and opening at low tide.

A number of other requirements and boundary conditions are taken into account:

From boring logs near Bolivar Roads it becomes clear the soil in Bolivar Roads consists mainly of soft and firm clay layers before reaching a strong bearing sand layer at MSL-40m.

In the near future the port of Houston demands the passage of the New Panamax tankers through Bolivar Roads. To accommodate these the channel will have to be dredged to a depth of 17m and allows a free passage of at least 220m wide. These numbers are determined using the rules for shipping channel dimensions by PIANC-IAPH (1997). Closure of the barrier earlier than 27 hours before landfall likely results in hindrance of navigation (personal communication 27-5-2014, R.W. Welch, VTS Houston). About 27 hours before landfall the majority of navigation will come to a hold. Navigation will be resumed not earlier than 2 days after landfall. The moment of opening the barrier after a closure is therefore not decisive.

Due to the large size of the Galveston Bay, there might be an opportunity to construct a barrier that is only partly retaining the water, leading to cost savings. Several options have been considered, such as only partly constructing a barrier over the length of the Bolivar Roads (called a reduction barrier), allowing flow under the gates (with a ‘hinge gate’) and overflowing by lowering the crest. For the conceptual design the final option (lowering the crest) has been chosen, as this seemed to provide the least technical difficulties and the lowest costs.

The barrier shall affect the Bay’s hydrodynamics slightly in regular conditions. A decrease in flow area (constriction) at Bolivar Roads affects the tidal range and tidal prism of the Bay, influencing the water circulation in the bay and thereby the ecosystem. If the flow opening in Bolivar Roads becomes less than 60% of the original the Bay’s ecosystem is adversely affected (Ruijs, 2011). In the conceptual design an opening of about 70% is aimed for.

The storm surge barrier shall be designed to protect against surge levels with a return period of 1/10,000 yr^{-1}. Based on a preliminary cost benefit model, it is found that this protection level gives the highest rate of return (Stoeten, 2013). The structure is designed for a 200 year lifetime; comparable to the Eastern Scheldt Barrier in the Netherlands and the IHNC Lake Borgne Barrier in New Orleans.

Design of the navigation section

To accommodate shipping through the Bolivar roads a width of 220 meters, a depth of 17 meters and unlimited headway is required. The most suitable gate types for the storm surge barrier with the large span in the navigation section are a barge gate (see fig. 5, left) and a sector gate, which was applied for the Maeslant barrier) (see fig. 5, right).

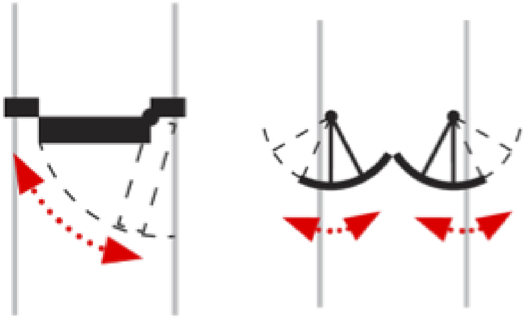


Figure 5: Barge gate (left) and sector gate (right)

A major disadvantage of applying sector gates to this case is that they cannot easily deal with negative hydraulic heads. A floating barge gate is a more suitable solution for negative heads, as it would simply ‘re-open’ without any significant damage.

The closure procedure of a barge gate is less complex as only one gate has to be closed compared to two in a sector gate system. Furthermore, the hinge required for a barge gate is less complex then for a sector gate. The hinges of the sector gates have to transfer the maximum load to the foundation, whereas loads for the barge gate are partly distributed to embankments (ee below). Finally the space the barge gate occupies during recess / normal conditions is much smaller than for a sector gate. Therefore a barge gate is preferred for this application, see figure 6.

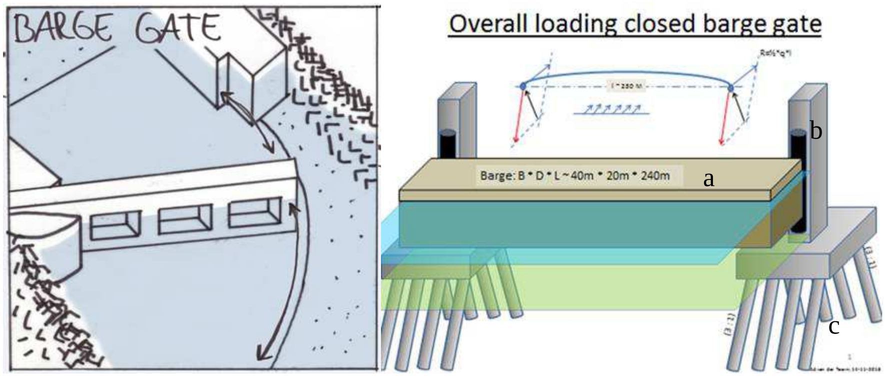


Figure 6: Impression of the barge gate (left) and proposed gate in the next phase of the study (right) (Jonkman et al., 2013).

A conceptual engineering design of the gate has been made (fig. 6 right). The barge gate in the Bolivar roads (‘a’ in fig. 6 right) will distribute the horizontal forces towards the embankments on the side of the ship channel (‘b’). The barge gate contains valves within the main gate for stability during closure. Because of the poor soil conditions in combination with the underwater working conditions a deep pile foundation (‘c’) or a deep foundation realized by (pneumatic) caissons or cellular cofferdams are possibilities for the foundation of the barrier. The proposed barge gate can consists of a steel or (pre-stressed) concrete structure.

Design of the environmental section barrier

In an initial stage a shallow-founded caisson barrier with vertical doors appeared to be the most appropriate barrier type for the environmental section (de Vries, 2014). The crest level has initially been set on MSL to allow some overtopping and a lighter structure, but this requires more detailed investigation. In total, the environmental section included 338 gates each spanning 6.7 meters. The sill depth follows the present bottom profile and is MSL – 9.7m on average. It decreases the flow area down to 68% of the original. The choice for caissons was based on their ability to spread the loads over the soil. However, during the design process it was concluded that the settlement of the clay layers underneath the caissons were too large, thus requiring additional measures such as vertical drainage (see Fig. 7). Underwater installation of vertical drains is expensive and there is limited experience with it. An alternative deep foundation is preferred as it solves the settlement issues through directly transferring the loads to the bearing sand layers. Given the foundation issues, other alternatives for the environmental barrier should be investigated as well, including a wide-footed T-wall construction on a deep foundation. This may emerge as an alternative as it is requires less material than a caisson. In a more detailed stage of the design process these foundation types will be considered.

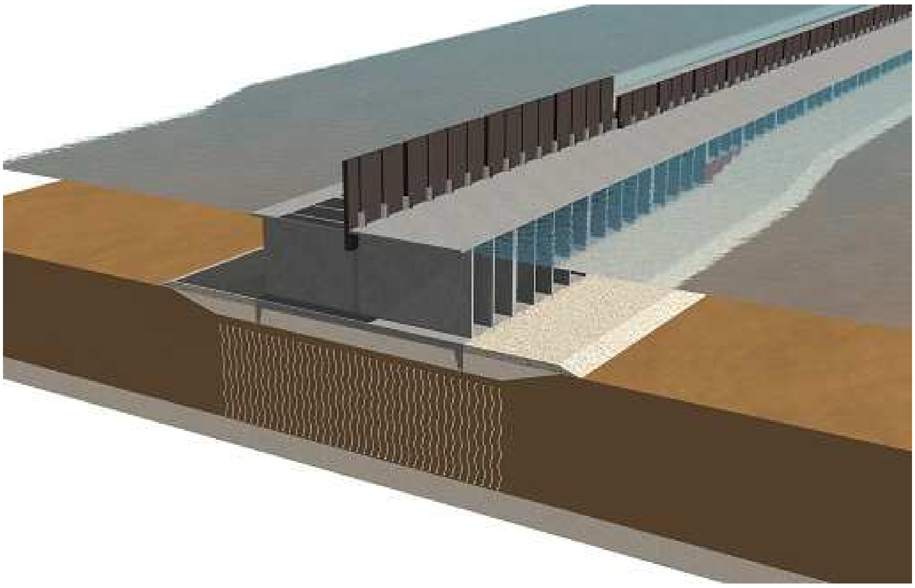


Figure 7: Birds eye sectional view of caisson barrier with vertical drain soil improvement (de Vries, 2014).

CONCLUDING REMARKS AND FUTURE CHALLENGES

The Houston Galveston is at significant risk from coastal surge flooding. This study has focussed on the Ike Dike, but other strategic alternatives for flood risk reduction for the region are under consideration. These include a “perimeter protection” approach around the bay, consisting of several features such as levees, wetlands and a local storm surge barrier near Houston (Blackburn et al., 2014). Eventually, various strategic alternatives would have to be elaborated. Then they can be compared on aspects such as costs, flood risk reduction, societal, ecological and economic impacts, as a basis for decision-making on future flood risk management in the region.

A coastal flood risk model would provide a basis for evaluating the effectiveness of various strategies for flood risk reduction. A simplified probabilistic model has been developed to determine return periods of surge under various regimes of interventions. It can be improved by a more rigorous analyses of hurricane surge and the associated return periods. To assess the flood risk the return periods of surge flooding need to be coupled to land use and damage models. This will provide a) a basis for damage and risk assessment and an indication of hotspots; b) a basis for evaluation of risk reduction options. The risk framework can also be used to determine the optimal level of protection that would be justified given the costs and benefits of risk reduction (see Jonkman et al., 2009 for an example for New Orleans).

As part of the Ike Dike system optimization the cost effectiveness of different retaining heights of the surge barrier could be investigated in terms of (barrier) cost savings vs. additional flooding and intervention costs in the bay. Another important aspect for further study concerns the environmental impacts of potential barriers on the flow regimes and ecological systems in the Galveston Bay. As part of the Ike Dike system, land barriers on Galveston island and the Bolivar peninsula would have to be designed. Several types of dikes / levees could be investigated and it needs to be investigated whether these land barriers can be overtopping resistant or whether they should block the surge. Integration of new defence concepts in the urban and rural landscape also requires further study and design.

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