# Probabilistic design of breakwaters in shallow, hurricane-prone areas

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## Introduction

One of the failure mechanisms of a rubble mound breakwater is the failure of its armour layer. In order to determine the stability of an armour layer, the design load has to be defined, which is in fact the wave that attacks the structure. Being a highly stochastic phenomenon, the wave action is not easily defined, while there is always some uncertainty inherent to its definition. In a deterministic calculation this uncertainty is being left to engineering judgment, as the possible variations of the design wave height are not taken into account in a coherent way. In order to explicitly incorporate uncertainties into the design process, and therefore increase its reliability, probabilistic design methods should be applied. A commonly used approach is a semi-probabilistic computation, which introduces the application of partial safety coefficients. Nevertheless the indicated methods to derive and apply them do not clarify the uncertainties incorporated, adding an undefined degree of safety in the process, or end up with incorrect results under certain conditions. Another approach is a fully probabilistic computation. This type of design tackles explicitly a great deal of uncertainties, hence its results can be considered much more accurate. However it is not commonly used, due to the fact that there are not straightforward guidelines to support it, and therefore a number of critical decisions by the designers are required.

This paper focuses on the application of probabilistic methods for armour layer design of rubble mound breakwaters. The main objective is to indicate the weaknesses of the previously mentioned methods, and to suggest a probabilistic design approach that is both attractive to designers and sufficiently reliable. This can be achieved through elaboration of a design example with the various methods, followed by a critical evaluation of the results.

## Case study description

The example application, through which a critical assessment of the design methods can be realized, needs to concentrate some particular characteristics that facilitate this process, and create a strong basis for the development of a new design approach. An interesting case for demonstration is the jetties at the entrance of Galveston Bay, which is a large estuary located along the upper coast of Texas in the Gulf of Mexico (figure 1). The main function of the structures is to stop siltation at the entrance of the estuary, but they must also be able to resist occurring waves. They are part of the network of structures that protect not only the port of

Galveston, but also the vital industrial shipping facilities in and around Galveston Bay, where a significant amount of America's oil and chemicals are produced.

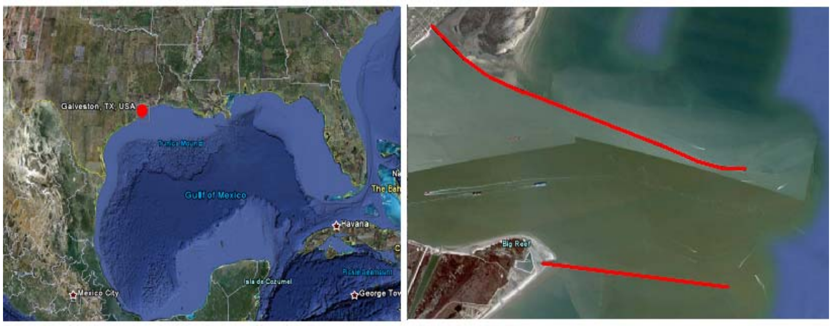

Figure 1: Location and footprint of Galveston jetties

The features of interest on which the choice of case has been based, are first the hurricane-dominated hydraulic climate of Galveston, and second the fact that the structure is located in relatively shallow waters. Both characteristics generate a number of drawbacks in the design process, which allow for a thorough overview of the way that each method deals with them. The existence of hurricanes imposes a lot of uncertainty in the definition of the design load and the design process, which has to be taken into account. The shallow water implies that the structure is attacked by depth-limited waves, which likewise, cannot be disregarded in a design.

## Hydraulic climate

The hydraulic processes that take place along the coasts of the Gulf of Mexico are affected in a high rate by the occurrence of hurricanes. Depending on the bathymetry, hurricanes contribute in the occurrence of extreme storm surges and waves, which, in combination with other unfavourable conditions can contribute in the determination of the hydraulic boundary conditions in a particular area. The general hydraulic climate can be described with the following conceptual framework of hydraulic processes.

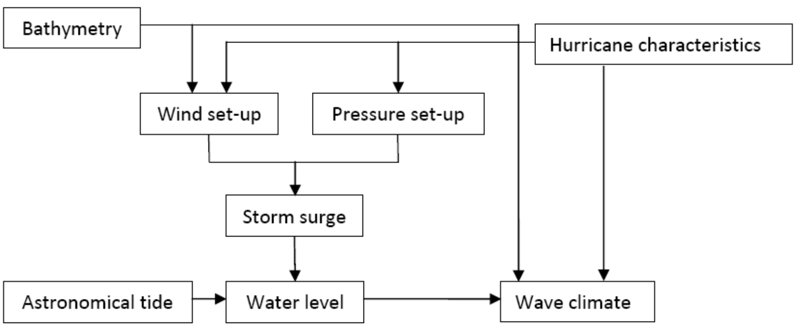


Figure 2: Framework of hydraulic climate (Maaskant, Van Vuren, Kallen, 2009)

Based on this framework, the design conditions can be derived, which are the design wave and water levels at Galveston. In order to determine the aforementioned parameters some local data need to be analysed. The data available for Galveston are some local bathymetric maps, hurricane records for the period 1850-2009, and storm wave data supplied by Argoss[1]

[1] www.waveclimate.com

database and Global Wave Statistics (Hogben et al, 1986). From hurricane records, information about hurricane-induced waves is extracted, while from Argoss and Global Wave Statistics information about normal storm waves can be gained. It is noted that except for the action of short waves, the action of swells is also taken into account, whose energy can have considerable effect to the hydraulic load. Based on the records, exceedance probability curves are produced for the various types of waves. The most unfavourable design conditions are indicated by hurricane-induced short waves.

## Elaboration of design

The design presented below concerns a rubble mound breakwater, which is assumed to be the optimum solution for Galveston area. The design focuses on the stability of its armour layer. In total three designs are elaborated with three different methods; 1) a deterministic design, 2) a quasi-probabilistic design with a method indicated by PIANC (1992), and 3) a fully probabilistic design with a Monte Carlo simulation. As design equation the stability formula of Van der Meer for plunging waves in shallow waters is used (Verhagen, Mertens 2007). An analytic description of the parameters included in this equation can be found in the references. Apart from the significant wave height $H_{2\%}$, all parameters are consistent in the three designs. The determination of design wave height, which is the main load parameter, is not consistent in the presented methods. This is the key element of difference of the three designs.

### Target probability of failure

An economic lifetime for a breakwater is in the order of 50 years; hence a lifetime of 50 years is chosen. During lifetime, a probability of failure equal to 20% is assumed to be acceptable for a structure functioning as outer breakwater, like Galveston jetties. This probability corresponds to a yearly probability of failure equal to 0.4%, and to a return period of design storm of 225 years. In reality the target probability of failure is chosen by means of economic optimization. This issue is out of the scope of this research, hence not elaborated. According to the above failure considerations and the available exceedance curves, the hydraulic boundary conditions can be determined.

### Deterministic design

The classical method for designing a breakwater is application of all the common dimensioning rules with the use of deterministic values for all parameters. The wave characteristics derived from hurricane and wave records refer to deep-water conditions. As the jetties of Galveston are located in relatively shallow water, the design wave is limited due to breaking. For this reason the deep-water wave data cannot be used directly in the design, but they need to be transformed to shallow water. This is possible with the use of SwanOne software (Verhagen et.al, 2008). The local tide and storm-surge are included in the input parameters of SwanOne modelling. For these parameters average values are used based on local data. Substituting the correct parameter values into Van der Meer equation, an armour unit of 10-15 tones proves to be appropriate. The type of loading that determines this design is hurricane-induced short waves.

### Quasi-probabilistic design (PIANC method)

An alternative method for design of a breakwater is the method of partial safety coefficients, which was worked out by PIANC (1992). This method introduces the use of safety factors for load and resistance in the armour stability formula, which is the equation of Van der Meer. According to the manual of PIANC the applied factors depend on the wave height distribution, which is supposed to be an extreme value distribution. This is in fact the case for deep-water conditions. Provided that no distinction is made concerning application of the method in deep and shallow water, an extreme value distribution of the wave height is assumed to be representative for Galveston as well. Based on this assumption, the safety factors are calculated with the formulae indicated by PIANC. For the parameters of Van der Meer equation, deterministic values are used as indicated for the deterministic design. The local tide and storm-surge are not needed for application of this method. The result is an armour unit of 60 tones. This design is also determined by hurricane-induced short waves.

Compared to the previously presented deterministic design, the method of PIANC results in an extremely larger armour unit. Although it is still not clear which of the two results is more appropriate, it can be already concluded that the latter result cannot be correct, due to the fact that the assumption of an extreme value distribution of the wave height is not correct in shallow waters, where wave breaking takes place. In this case the exceedance curve of the wave height cannot increase infinitely like in deep waters, but there is a point that it becomes constant (figure 2). This variation of the exceedance curve cannot be taken into account with the PIANC method.

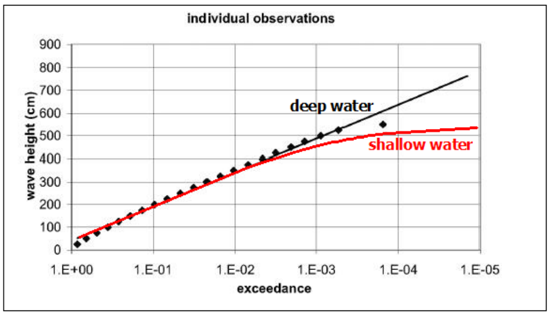


Figure 2: Exceedance curves of wave height in deep and shallow waters

## Fully probabilistic design (Monte Carlo simulation)

The application of a fully probabilistic computation is the design method that deals explicitly with all uncertainties. This computation can be performed with a First Order Reliability method or Monte Carlo simulation. All simulations can be elaborated with appropriate MATLAB routines. A Monte Carlo simulation is chosen for Galveston jetties, as it is more accurate than a First Order Reliability method. According to it the results of the previously presented designs can be assessed.

The limit state function is as follows:

$$Z = c_{pl} \cdot P^{0.18} \left(S/\sqrt{N}\right)^{0.2} \left(s_{m-1.0}\right)^{0.25} \sqrt{\cot\alpha} \cdot \Delta d_{n50} - H_{2\%} \quad (1)$$

The wave height $H_{2\%}$ is the parameter with the highest degree of uncertainty in this function. In deep waters the wave height follows an extreme value distribution. In the case of Galveston that the water is shallow, the wave height can be approximated to a function of the water depth h. As water depth h the total depth is considered, i.e. the depth below mean sea level $h_d$, plus the rise of water level due to tide $h_t$ and storm surge. The surge in shallow water is a function of different parameters depending on the hydraulic conditions that are examined each time. If a hurricane pass is the determining design condition, which is the case for Galveston, the surge is defined as the sum of wind set-up $h_w$ and pressure set-up $h_p$ (equation 2).

$$H_{2\%} = \gamma_b H_{surge} = \gamma_b (h_t + h_p + h_w) \qquad (2)$$

The wind and pressure set-up are functions of many other parameters, among which some hurricane parameters exist. The hurricane proves to be sufficiently described by three uncorrelated variables; its speed u, the angle of its trajectory β, and the distance between its landfall and the design spot C. These three variables contribute the highest degree of uncertainty in the process. The wave height ends up being a function of 20 variables, while the limit state function ends up with 28 uncorrelated variables (Tsimopoulou, 2010).

In order to run a Monte Carlo simulation, a probabilistic determination of all variables is necessary. This means that their distributions have to be defined. After thorough investigation of each variable separately, their best-fitted distributions have been concluded. This information comprises the input for running the simulation in MATLAB. The output is a probability of failure for a certain armour unit size, which is represented in the stability formula by the nominal armour unit mass $M_{50}$. Following a trial and error procedure the armour size corresponding to a probability of failure equal to the target $P_{f,lifetime}$=20%, can be derived. The appropriate unit size is 48 tones. This is a size that cannot be achieved with rock units, but artificial concrete units should be considered instead. Moreover this result is different from the results of the previously presented designs. By entering the unit masses of the deterministic and PIANC design, probabilities of failure other than 20% are extracted. The result of the trial and error procedure is shown in the graph below.

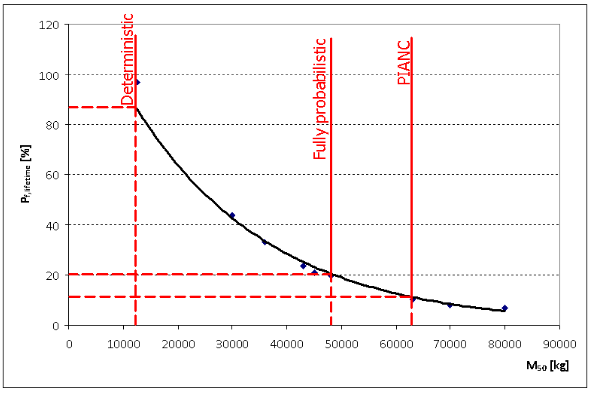


Figure 3: Design results

## Assessment of results

In the above graph it is clearly shown that the results of the three elaborated designs are totally different. Considering the substantial differences of the three approaches, such a divergence of results was expected. These differences can be identified in three points: 1) the definition of safety level, 2) the determination of load, and 3) the deep and shallow water considerations. Given the fact that the fully probabilistic approach deals explicitly with the major uncertainties inherent to the design process, it is assumed to be the most accurate one. Based on this assumption the classical deterministic design is not sufficient, as it is almost certain that the structure will fail during lifetime. On the other hand, the design with PIANC method is quite conservative, since the resulted probability of failure during lifetime is about 50% lower than the target. This result was expected, since as mentioned before, the PIANC method gives incorrect results in cases that depth-limited waves determine the design load.

## New design approach

In all the above presented design methods there is a contradiction between two equally important qualities; the reliability of the extracted results and the ease of use of the method itself. This contradiction can be the starting point for the development of a design approach, whose objective could be the optimum combination of the two qualities. Based on the elaborated designs, in areas like Galveston, where a high degree of uncertainty is present in the design process, a sufficiently reliable result is only feasible with a probabilistic computation. In order to have an easily applicable probabilistic method, a quasi-probabilistic computation is suggested, with the use of partial safety factors in the design equation. The concept of safety factors is a certainly effective method for designs that involve a lot of uncertainty like breakwater designs, while also very practical and easy to apply. It is commonly used in building codes, such as the Eurocodes. However, in many cases the degree of uncertainty incorporated by the factors is not well defined, leading to incorrect results. The method of PIANC applied in Galveston is an example of a quasi-probabilistic computation with incorrect results. For the case of Galveston a fully probabilistic design has already been presented, in which all uncertainties have been explicitly indicated. Although there are improvements to be made in the model used for the fully probabilistic calculation, it is assumed that its results are sufficiently reliable, and therefore they can be used as a basis for calibration of a new set of safety factors. Calibrating the new factors with respect to the results of Monte Carlo means that the outcome of the new approach will be the same as a fully probabilistic computation. The analytical steps for deriving the safety factors are presented below. It is important to note that the following steps are meant to be elaborated by code-makers rather than designers, while designers are expected to use the extracted safety factors in a proper way in order to achieve reliable designs.

### Safety format

In order to derive the safety format, the scope of the new approach needs to be defined. This is to create a reliable and handy set of safety factors, which will cover an important degree of the uncertainty inherent to the physical problem and the design. In order to have a handy tool, the number of safety factors should be reduced to the minimum possible. Its reliability can be maximized if the maximum possible degree of uncertainty is incorporated. The least number of safety factors with which the maximum degree of uncertainty is incorporated is two: one factor for the total load, $\gamma_S$, and one for the resistance, $\gamma_R$. The stability formula takes the following form:

$$\gamma_R R - \gamma_S S = 0 \tag{3}$$

where R and S are the total load and resistance respectively, and can are defined as follows:

$$S = \gamma_b (h_t + h_d + h_p + h_w) \tag{4}$$

$$R = c_{pl} P^{0.18} \left( S/\sqrt{N} \right)^{0.2} (s_{m-1.0})^{0.25} \sqrt{\cot\alpha}\,\Delta d_{n50} \tag{5}$$

All the uncertainties covered by the load safety factor are connected with load parameters. There are still some uncertainties related to the load which are not dealt with the load safety factor, the ones inherent to the wave steepness and the number of waves. These parameters are included in the resistance term of the chosen limit state function, and therefore incorporated to the factor of resistance. Also uncertainties associated with the probabilistic model are not incorporated in the safety factors.

## Calculation of load safety factor

The safety factor for load is defined as the ratio of the design load $S^*$ over the characteristic load $S^k$:

$$\gamma_S = S^* / S^k \tag{6}$$

The design load can be calculated with the fully probabilistic model. In particular, based on information used as input in Monte Carlo, a new fully probabilistic calculation of the total load can be elaborated in MATLAB with a new Monte Carlo simulation. The outcome is an exceedance curve of the load, which is supposed to be the one with the highest possible accuracy, as all uncertainties have been incorporated in a satisfactory way. Therefore, they can be used as design values, while a set of satisfactory results of a semi-probabilistic calculation should converge to the outcome of this simulation.

The limit state function for the new simulation is the following:

$$Z = S - \gamma_b (h_t + h_d + h_p + h_w) \tag{7}$$

Where S = total load, while the rest of the parameters are already known. There are in total 12 variables in the above function. For every particular deterministic value of the total load, a probability of failure is extracted, which is in fact the probability that the Z-function becomes negative. By giving various deterministic values to the total load, a design exceedance curve is created.

If in the above simulation some of the variables are replaced by deterministic values, the outcome will be a different exceedance curve. This difference is indicative of the degree of uncertainty inherent to those particular variables, which is supposed to be incorporated by the safety factors. Using deterministic values for all the load variables, the total load becomes deterministic too, and the exceedance curve turns to be a straight line parallel to the x-axis. In order to come up with a line that represents the characteristic exceedance curve of the total load, all chosen deterministic values of the variables need to be their characteristic values. Since there is no standard rule for the choice of characteristic values, but they vary in different designs depending on the overall design approach, a choice for all the load variables is necessary, which can be reasonably substantiated. The most commonly used choices for characteristic values are either mean variable values or values with probability of non-exceedance equal to 95%. For this project mean values are chosen for the majority of variables, in accordance to PIANC (1987). It should be noted that the choice of characteristic values is not critical for the final design. A different set of characteristic values would result in a different set of safety factors; the same degree of uncertainty would always be incorporated though.

The design and characteristic exceedance curves are presented in figure 4. Using values of this graph, the load safety factor can be easily derived from equation 6. This factor accounts for the uncertainties that are neglected when the design parameters take deterministic values, and literally constitutes a measure for the divergence between the characteristic and design exceedance curves.

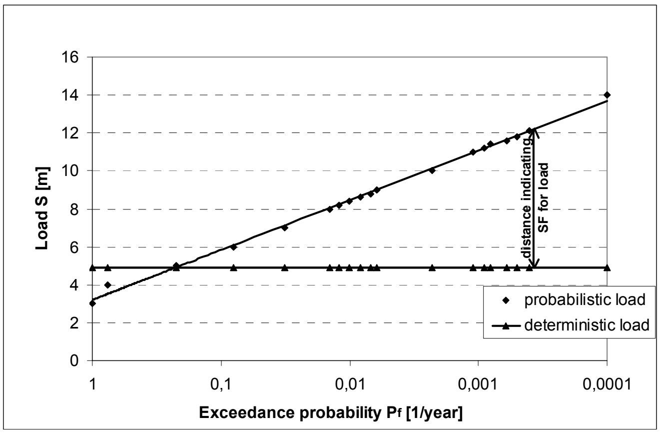


Figure 4: Design and characteristic exceedance curves

## Calculation of resistance safety factor

The safety factor for resistance is meant to incorporate uncertainties inherent in the resistance parameters of the stability formula. In this case, the concept of exceedance curves makes no sense, as all resistance parameters are related to design and construction, and therefore their degree of randomness is a matter of choice. For this reason, the resistance factor is derived with an iterative process for certain discreet probabilities of failure, once the design hurricane and load factor are specified. This process is summarised in the following steps.

1. Calculation of characteristic load $S^k$, using the design hurricane values for all hurricane parameters, i.e. u, β, C, and mean values for the remaining load parameters.
2. Calculation of design load with equation 6, using the selected load safety factor $\gamma_S$.
3. Application of Van der Meer stability formula for calculation of characteristic nominal armour unit mass $M_{50}{}^k$, using mean values for all resistance parameters. The definition of mean values is the same as in step 1.
4. Validation of process through a Monte Carlo simulation. The limit state function is equation 1. All resistance input parameters are deterministic, $M_{50}{}^k$ for the nominal unit mass and mean values for the remaining parameters. The load parameters are inserted as random variables, with their own distributions, as determined before. The extracted probability of failure has to be equal to the target probability of failure.
5. Actual derivation of resistance safety factor with a trial and error procedure, applied in a Monte Carlo simulation, with limit state function corresponding to equation 3. All resistance and load parameters are inserted as random variables, except for the nominal mass, which takes the characteristic value calculated in step 3. The safety factor $\gamma_S$ is inserted as constant and its value is already known, while the resistance safety factor $\gamma_R$ is the trial parameter. Starting with $\gamma_R$=1, a probability of failure is calculated, which is higher than the target probability of failure. The simulation is repeated with gradual increase of $\gamma_R$ until the target probability of failure is reached.

Once the resistance safety factor is derived, the design nominal mass is calculated as follows:

$$M_{50}{}^{*} = \gamma_R M_{50}{}^{k} \tag{8}$$

### Sensitivity analysis

The final values of the safety factors depend to an important extend on the designers' choice of characteristic values for the various variables. Through a first order reliability method simulation in MATLAB, it is concluded that the probability of failure of the structure is determined in a high degree by two load variables, the hurricane speed u, and the distance between the hurricane landfall and the design spot C. As both parameters are connected with the hurricane, their variation is very high. For this reason a sensitivity analysis is performed and different values of load safety factors are extracted for the various values of the two parameters. Some indicative results of this analysis are presented in the graphs of figure 5.

According to the graphs the load factors increase as the target failure probability becomes lower. It is also perceptible that for higher hurricane speed the load factor decreases, meaning that when a higher design hurricane is used then a lower safety factor is needed. Both conclusions were expected. From the variations of parameter C, the most unfavourable hurricane landfall can be concluded, which is the one requiring the highest safety factor. All curves are maximized for C=-5000, which corresponds to a hurricane with landfall 5 kilometres to the south of Galveston jetties.

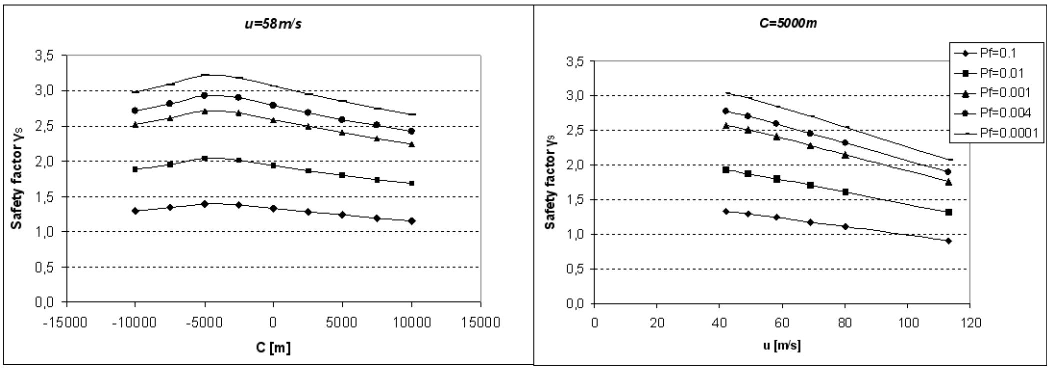


Figure 5: Load safety factor for variations of hurricane parameters

## Concluding remarks

Based on this research a number of concluding remarks have been drawn and are summarized below with respect to the various issues that have been examined.

### Design methods

- In a deterministic design uncertainties are only dealt implicitly, as the choice of all design parameters is un-prescribed and relies only on engineering judgement. Therefore the assigned safety level is not clearly defined; hence there is always a risk of insufficient designs results.
- The design of PIANC results in extremely high values for the armour unit mass. This is due to the fact that depth-limitations in the wave height are not taken into account in the method, and therefore incorrect results are extracted in case of shallow water designs, like Galveston jetties.
- A fully probabilistic computation deals explicitly with the majority of uncertainties inherent to the design, and therefore it can be considered the most reliable design method.

### Suggested design approach

- The new approach is a quasi-probabilistic design method. The main accomplishment of the new development is that an easy to apply quasi-probabilistic method results to equally

reliable designs with a fully probabilistic method, as it incorporates the same uncertainties.
- The procedure for deriving the new safety factors is generic and can be used as a guideline for code-makers.

### Safety factor values

- The derived safety factors are site-specific, because a site-specific probabilistic model is used for their calibration, which is the model created for the fully probabilistic design of Galveston jetties. A generic set of safety factors should be appropriate for use in a greater area than just Galveston, e.g. the entire Gulf of Mexico. Hence a generic use of the safety factors requires incorporation of results of a number of different case studies.
- The load safety factor is basically a function of hurricane parameters. If a different design hurricane is used in a design, then the safety factors take different values.

## Recommendations

- In all stages of the performed analysis a number of simplified assumptions have been made, many of which have not been validated. As a consequence, the reliability of the extracted results and the follow-up conclusions can be questioned. An optimization of the total analysis is therefore necessary, which can be achieved through reconsideration of all weak points that limit the value of the overall outcome.
- In order to derive safety factors that can be used for generic breakwater design more case studies need to be conducted. As different locations have different hurricane characteristics and bathymetry, the derived safety factors will have different values. The result of different case studies will be a scatter of safety factors. Subsequently, one safety factor suitable for a greater area than just Galveston could be chosen.
- A validation of the performed analysis is necessary. This can be done with its application in a new location with similar hydraulic features, such as the coast of Vietnam.
- Based on the new sets of safety factors, a guideline for future designers could be developed, containing indication of safety factor values in different locations.

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