Robust Optimization for Stability of I-Walls and Levee System Resting on Sandy Foundation

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ABSTRACT

During Hurricane Katrina in 2005 and the events thereafter, failures of levees with I-walls caused extensive flooding and damage. The geological background in the New Orleans area and associated uncertainties contributed significantly to the failures. To increase the robustness of the I-walls and levee system and reduce the associated risk of failure, the uncertainties of the system must be incorporated into the design procedures, especially in a geological environment mainly composed of sand deposits. This paper presents a robust optimization procedure to identify optimal designs for the stability of an I-walls and levee system supported on sandy foundation soil in the face of flood hazards. The uncertainties associated with the I-walls and levee system, including the strength parameters of levee and foundation soils and the height of the floodwater behind the I-walls, were considered in a systematic manner. The wall embedded depth, levee crown width, and slope ratio of the levee in the landside were considered as the design parameters. For the robust optimization, the construction cost of the I-walls and levee system and the standard deviation of the failure probability were considered as the design objectives. Finally, the multi-objective optimization resulted in a set of acceptable designs that were presented in a graphical form called Pareto front, which is combined with the knee point concept to provide useful decision aids for selecting the most preferred design that meets both the economics and performance requirements.

Keywords: Uncertainty; Levee; Stability; Robust Optimization; Finite Element Method

1. INTRODUCTION

Typically, levees with or without floodwalls are designed using deterministic methods considering the site-specific geotechnical and extreme hydrological parameters. The conventional approaches for designing such hurricane protection systems are typically based on the performance of an individual component of the system, and the factor of safety is used to address the uncertainties in such design approaches (Sills et al. 2008). Therefore, a more comprehensive probability-based approach that integrates the individual components of the system is needed to evaluate the impacts of the uncertainties on the system performance. In this study, a response-surface-based probabilistic design approach was developed and implemented to systematically account for the uncertainties and quantify the failure probability of the system and the associated variations. The approach can explicitly incorporate the reliability, robustness, and cost-efficiency of the design in the optimization process.

The sudden and uncontrolled failure of critical levee systems may result in severe flooding which causes significant economic and human losses (Flor et al. 2010; Yang et al. 2011). The failure of such systems usually occurs due to the exceedance of water elevation above the levee crown and/or overestimation of the strengths of levee and foundation soils. However, increasing the capacity of such flood protection systems and protecting the landside from the overflow of water can be achieved through expanding the levee section or floodwall installation. Expanding the levee section is not considered as a reasonable option where there is a limited right of way on the landside or the existing foundation is not suitable for additional levee load. Fig. 1 shows the levee section and the additional space needed to expand the levee section which may not be available in many situations. In such situations, a floodwall is commonly used to increase the capacity of the levee.

There are two types of floodwalls, as shown in Fig. 2: I-walls and T-walls. The I-walls are I-shaped walls typically consisting of sheetpile walls driven into the levee and concrete caps fixed to the top of the sheet piles above the levee crown. The T-walls are like gravity-cantilever retaining walls that resist the flood load by cantilever action. Because of the complexity in the design and construction of T-walls, I-walls are commonly used in practice.

Flooding caused by the failure of an I-walls and levee system protecting highly populated and high-valued real estate areas can be significant. The flooding caused by the levee failures after Hurricane Katrina resulted in billions of dollars in damage in New Orleans. Particularly, flooding in some areas was caused by the failure of I-walls and levee systems supported by the sandy foundation. It was also found that the geological history and depositional environment significantly affected the mechanical and flow properties of the foundation soil beneath the I-walls and levee system (Dunbar and Britsch 2008). Sills et al. (2008), Duncan et al. (2008), and the IPET (Interagency Performance Evaluation Taskforce) team investigated the failure mechanisms of I-walls and levee systems during Hurricane Katrina. They reported that the I-walls and levee system of the South London Avenue failed largely due to the piping that occurred in the sandy foundation. Centrifuge tests were conducted to evaluate the failure mechanism of the I-walls and levee system (Sasanakul et al. 2008 and Ubilla et al. 2008), and it is found that the layout of the levee geometry, the embedded depth of I-walls, and engineering characterization of soils contributed to the failure of the levee. It was recommended to increase the embedded depth of the sheet pile to increase the lateral support of the wall and decrease the flow of water through the sandy foundation.

In addition to the IPET, the ILIT (Independent Levee Investigation Team) also conducted a comprehensive site investigation and computer analyses on two-dimensional levee sections from several locations where I-walls and levee system failures were observed (Seed et al. 2008). The teams (IPET and ILIT) developed simplified two-dimensional cross-sections of the I-walls and levees found at the breach locations and analyzed them using the soil properties and storm-surge data measured from the site. They used coupled geotechnical-hydrological finite element software PLAXIS and limit equilibrium software. For the limit equilibrium analysis, IPET used SLIDE and UTEXAS and ILIT used SLOPE/W. Although these studies provide recommendations based on limited experimental and simplified numerical studies, a comprehensive study considering the uncertainties associated with the properties of the system and loading in the design of I-walls and levee systems is required. Also, the risk-based optimization studies conducted in the past only considered the uncertainties associated with the flood load. Moreover, most of the past levee design optimization procedures considered failures due to overtopping, and a few studies have included the geotechnical failure of the levees (Tung and Mays 1981; Hui 2014).

A reliable and robust design approach must not only consider I-walls, levee, and foundation as a single system but also consider the uncertainties associated with the system. Therefore, a probabilistic design approach needs to be implemented to achieve the reliability and robustness of the system. The reliability is ensured by evaluating the calculated failure probability to make sure it is less than the acceptable failure probability. Also, the robustness of the system refers to the reduction of design sensitivity to the effect of uncertainties in the system (Gong et al. 2014; Yu et al. 2019; Tan et al. 2020). Furthermore, the cost is explicitly considered as one of the design objectives to ensure the economics of the design. Generally, the cost is balanced with safety requirements using the factor of safety for the stability of the system in conventional deterministic design approaches while using the allowable failure probability in probabilistic design approaches. This paper provides a robust design scheme to optimize the cost and robustness of the I-walls and levee system, and the results of the robust design were compared with the non-robust design results. Also, for demonstrating the effect of variation of water elevation behind the floodwall on the I-walls and levee system design, several parametric studies were carried out considering the safety and failure probability.

2. DESIGN PROBLEM FOR STABILITY OF I-WALLS AND LEVEE SYSTEM

Defining the Problem and the Variables of the Study

For demonstrating the proposed design approach, an I-walls and levee system with clayed soils as levee materials and the sandy deposits as the underlying foundation was used in this study (Fig. 3). The levee crown cover materials are lime-treated clayed soils with negilible erodibilty. The floodside slope materials are well-compacted clayed soils with high plasticity, which has very low to negligible erodibility. The key factors affecting the system performance include both the design parameters and uncertain variables. The design parameters considered in this study are the embedded depth of I-walls (*D*), the levee crown width (*X*), and the slope ratio of the levee landside (*S*). The wall height beyond the crown of the levee (H_{ex}) is 2 m and the slope ratio of the floodside of the levee is 2H:1V. The uncertain parameters (also known as random variables) considered in the I-walls and levee system, including floodwater elevation behind I-walls (*wl*), undrained strength of the clayed levee soil (s_u), and angle of friction of the foundation soil (φ). Further details of the ranges and statistical properties of the variables are discussed in the following sections.

Design Parameters for Stability of the I-Walls and Levee System

One of the critical parameters for the I-walls and levee system's design is the embedded depth of the I-walls that has significant effects on the stability of slopes, control of seepage, and cost of construction. In deterministic design, to ensure that adequate embedded with considering the variations in soil properties, the minimum embedded depth (*D*) of the sheet pile wall shall be the greatest of 2.5 times the exposed height of the I-walls (H_{ex}) and 3 m below the levee crown (EC 1110-2-6066). The maximum value of H_{ex} is typically limited to 2 m for I-walls on levees or in soft soils (EC 1110-2-6066). Thus, in this study H_{ex} was kept remained constant at 2 m, and the lower and upper limits of *D* were assumed to be 2 m that is equal to H_{ex}) and 8 m, respectively (Rahbari 2017).

The levee crown width (*X*) was considered as another design variable due to its effect on slope stability. The lower and upper limits of X were assumed to be 3 m and 6 m, respectively. It should be noted that the same elevation (horizontal crown) was assumed for the flood side and landside of the levee crown in this study. The other design variable of the study is the landside slope of the levee. For levees made of clay and riverine levees in which the wave action is insignificant than the coastal levees, a steeper flood side can be used (EM-1110-2-1913). Therefore, the slope ratio of the floodside was fixed at 2H:1V and slope ratio of the landside (*S*) was varied between 2H:1V and 4H:1V. The design parameters of this study and their ranges are tabulated in Table 1.

Random Variables for Stability of the I-Walls and Levee System

The uncertainties in I-walls and levee system design arise from both resistance to failure and load. These include shear strength, deformation, and hydraulic parameters of the levee fill and foundation soils and the floodwater elevation. Since the levee fill and foundation soils are different in this study, the uncertainties associated with both soils must be considered. Among the many parameters, the undrained strength (s_u) of the clayed levee material and the angle of friction of the sandy foundation (ϕ) were considered as the soil-related uncertain parameters in this study. The floodwater elevation (wl) above the levee crown was considered as the loading-related random variable. The floodwater elevation varies between 0 and 2 m above the crown of the levee based on the limiting value of H_{ex} of 2 m. The statistical values for uncertain variables are listed in Table 2. The standard deviation values reported in Table 2 are determined based on the three-sigma rule and the range of the uncertain variables (Duncan 2000; Rahbari and Ravichandran 2018; Gao et al. 2019).

3. STABILITY ANALYSIS OF I-WALLS AND LEVEE SYSTEM

Stability Analysis Methods

Several limit equilibrium-based (LE-based) methods are available in the literature for evaluating the stability of an earth slope. These methods provide a factor of safety against failure (Coduto 1999; Chen et al. 2019). Between the mass procedure and method of slices, the method of slices is popular for computing the factor of safety of slopes with complex geometries and soil conditions. Among the many methods that utilize the method of slices, the Spencer method is used in this study.

Although the limit equilibrium-based methods provide a factor of safety against sliding and it is easy to conduct simulations, they do not provide any information about the deformation of the slope. Understanding the deformation behavior of levees, especially with floodwalls, is important because it can lead to the failure of the floodwall and result in the complete failure of the flood wall and levee system. In such situations, a finite element-based (FE-based) approach can be utilized to gain further insights into the behavior of the levee-floodwall system. The finite element-based method has become popular and widely for slope analysis that can provide realistic results in terms of system deformation and slope failure mechanism (Liu et al. 2018; Gao et al. 2019). In other words, finite element-based analyses are useful when it is necessary to capture the behavior of the soil and wall in a coupled manner with complex loading and geometric conditions. In the finite element-based programs, the slope failure occurs naturally in the system where the soil shear strength is unable to resist the shear stress (Griffiths and Lane 1999). One of the main FE-based slope stability analysis methods is known as the strength reduction method, in which the critical slip surface is sought based on shear strain increase due to the reduction in shear strength of soil (Chen et al. 2014).

Therefore, to analyze the overall stability and performance of the I-walls and levee system resting on the sandy foundation, both the FE-based program PLAXIS 2D and the LE-based program SLIDE were used in this study. The comparison of results obtained from these programs allows for evaluating the accuracy of the FS values, which can accordingly guarantee the accuracy of the failure probability computations. Thus, selected designs of the I-walls and levee system were chosen based on the feasible design domain and were simulated using the FE-based program PLAXIS 2D and the LE-based program SLIDE. The overall stability using PLAXIS 2D is computed through safety analysis in which the strength reduction method is applied for obtaining FS following the consolidation and plastic analyses. On the other hand, Spencer's method can be used for FS calculation in SLIDE (Rocscience 2016), which is a LE-based slope stability software with built-in finite element groundwater seepage analysis.

Stability Analyses Using LE and FE Procedures

In this study, the overall stability of the levee-floodwall system resting on a sandy foundation was evaluated using both the FE-based program PLAXIS 2D and the LE-based program SLIDE. For the LE-based analysis, Spencer's method implemented in SLIDE software was used. In the calculation, the soil mass above the slip surface is divided into a number of slices and both moment and force equilibrium of the sliding mass are satisfied in the analysis. A number of iterations are needed to locate the critical slip surface and ensure the complete equilibrium to obtain an accurate factor of safety. In SLIDE modeling, the stress-strain behavior of levee fill and the foundation soil was represented by Mohr-Coulomb material model, and the Infinite Strength material type was used for I-walls to treat the wall as a rigid component. For modeling steady-state seepage conditions, hydraulic boundary conditions were applied by setting the total heads at the flood side and landside of the levee system. The finite element seepage analysis for the steady-state condition is built into the SLIDE program. The simulation domain was spatially discretized into around 1000 elements using 6-node triangular elements. A sample SLIDE model of the levee-floodwall system is shown in Fig. 4.

For the stability evaluation using the finite element method implemented in PLAXIS 2D, the strength reduction method was adopted to assess the global FS (factor of safety) of the I-walls and levee system (Brinkgreve et al. 2015). In the strength reduction method, the shear strength parameters ($tan\ \phi$ and c or s_u) of the soil are successively reduced until failure of the system occurs. The total multiplier ∑Msf is used to define the value of the soil strength parameters at a given stage in the analysis:

$$\sum Msf = \frac{\tan \phi_{input}}{\tan \phi_{reduced}} = \frac{s_{u,input}}{s_{u,reduced}} \qquad (1)$$

where the strength parameters with subscript *input* refer to the properties entered in the material sets and those with subscript reduced refer to the *reduced* values used in the analysis. ∑Msf is set to 1 at the start of the calculation to set all material strengths to their input values. The value of ∑Msf at failure is considered as the FS of the system. Selecting a point in failure zone of the system, the FS curve can be plotted and the global FS can be determined (Brinkgreve et al. 2015).

The soil behavior in the finite element model was modeled using Mohr-Coulomb models and I-walls were modeled using linear elastic models (e.g., plate element for the sheet pile component and soil polygon for the concrete cap). The soil-wall interaction is incorporated in the modeling using interface elements. The concrete cap dimensions were obtained from the reports on the levee I-walls of London Ave canal in New Orleans, as shown in Fig. 5, which was also constructed on the sandy foundation (Burk & Associates, Inc. 1986). For the sheet pile wall material, properties of PZ-27 sheet pile were used, and the plate parameters in PLAXIS 2D were computed accordingly as listed in Table 3. Using Young's modulus (E) of steel, moment of inertia (I) value and the cross-sectional area (A) of the section PZ-27, the equivalent thickness (d) of the wall can be calculated to be implemented in PLAXIS 2D, considering h as the plate thickness and b as the plate width (=1m). Moreover, finite element models consisting of very fine finite element meshes with over thousands of triangle elements. A sample finite element model is shown in Fig. 6.

It should be noted that before performing the stability analysis using LE and FE procedures, nine subset designs, as listed in Table 4 based on the range of parameters in the design domain, were selected as design parameters. Regarding the simulation setups, the FS values of the I-walls and levee system were obtained using both methods for variations of design variables (min., mean, max.) and compared, as shown in Fig. 7. It can be observed that the two methods are in good agreement with each other. However, the results of PLAXIS 2D were adopted in the optimization approach of this study, as is discussed in the following sections.

Evaluating the Effect of Uncertainties on Stability of the I-Walls and Levee System

The effect of uncertainties (random variables) of the system (wl, ϕ and s_u) on the factor of safety (FS) of the I-walls and levee system was investigated in this section. For subset designs in Table 3, the variations of FS with a change in each random variable are displayed in Figs. 8-10.

It can be observed from these figures that the FS value is greater than the assumed minimum FS of 1.5 in all selected design combinations. However, the worst design combinations are not considered here for monitoring the effect of limiting values of each design variable independent from the other two design parameters. Overall, Figs. 8-10 show that I-walls and levee systems were more stable with greater depth of wall embedded, wider crown levee, and milder landside levee slope. Fig. 8 shows that an increase in floodwater elevation from the levee crown to the top of the wall results in a decrease in FS value. From Fig. 8(c) it can be concluded that the steeper the landside slope of the levee is, the design experiences a lower factor of safety and at high water elevation, the FS values are approximately close for variations of landside levee slope.

Figs. 9 and 10 show that the effects of the soil-related random variables, s_u of levee fill and φ of sandy foundation, on FS are opposite to that of floodwater elevation. With levee fill of higher s_u, the FS of designs with D_{mid} and D_{min} are similar, as shown in Fig. 9(a). Fig. 9(b) shows that the I-walls and levee system with a wider levee crown gives a slightly greater FS, however by increasing s_u the increase in FS is not significant for the three design cases (X_{min}, X_{mid}, X_{max}). Generally, Fig. 9 indicates that the variation in s_u of the levee fill has a minor effect on the overall stability of the system comparing to the other random variables. As shown in Fig. 10(a), at low φ

the FS of design with minimum wall depth is close to that of medium depth. From Figs. 10(b) and 10(c), it can be noticed that in terms of levee crown width and landside slope variation of FS with a variation of φ follow similar trends. Overall, along with evaluating the variation of FS with random variables, the observed variations of FS itself due to variations of uncertainties can provide reasonable justification for selecting those governing random variables.

4. RESPONSE SURFACE-BASED PROBABILISTIC EVALUATION OF I-WALLS AND LEVEE SYSTEM

Response Surface for the I-Walls and Levee System

The traditional probabilistic design approach requires numerous finite element simulations and is computationally cumbersome (Goh et al. 2017; Zhang et al. 2019). The response surface method (Wong 1985; Zhang et al. 2017; Zhang et al. 2020) is an efficient approach to express the FS of the overall stability of the I-walls and levee system as a mathematical function of design parameters and random variables. The response surface method has been demonstrated as an effective tool for the reliability analysis of complex geotechnical problems through approximating the implicit numerical solutions (e.g., finite element model) with explicit and computationally efficient mathematical models (e.g., Wong 1985; Zhang et al. 2015; Zhang et al. 2020). Among the common models used in the response surface method (Khuri and Mukhopadhyay 2010; Zhang et al. 2015), the second-order polynomial model was used as shown below in this study:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 \qquad (2)$$

where y and x_i denote the response and input variables, respectively and b_0, b_i and b_{ii} are the coefficients determined from the central composite design based regression analysis. Using the model in Eq. 2 via the regression analysis between the input variables and the response, the response surface to evaluate the FS for the overall stability of the I-walls and levee system can be determined as:

$$FS = 0.7756 + 0.0134\phi + 0.0513s_u - 0.3324wl + 0.0554D + 0.0451X - 6.7437S$$
$$+0.0013\phi^2 - 0.0006{s_u}^2 - 0.0559wl^2 + 0.0033D^2 + 0.0050X^2 + 5.4571S^2 \quad (3)$$

A number of random design sets combined with randomly selected uncertain parameters were generated to validate the response surface. The calculated FS values from the response surface were compared with those obtained from the finite element simulations, and the resulted coefficient of determination (R^2) value for the built response surface function equals to 0.968 (1.0 being the highest possible value that indicates the perfect agreement). To evaluate the accuracy of the developed response surface quantitatively, three quantitative indicators recommended by Moriasi et.al (2007) were adopted for comparing the simulation results (i.e., results from SLIDE) with the observed results (i.e., results from response surface). The indicators used in this study are the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR) that are shown in Eqs. 4, 5, and 6, respectively.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{mean} \right)^2} \right] \quad (4)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) * 100}{\sum_{i=1}^{n} Y_i^{obs}} \right] \quad (5)$$

$$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right]} \tag{6}$$

where Y^{obs} is the observation (FS from PLAXIS 2D), Y^{sim} is the simulated value (FS from response surface) and Y^{mean} is the mean of observed data. These validation statistics were computed, and the performance of the response surface was rated per Table 5. The overall performance was described as Very Good, and therefore, the mathematical model presented in Eq. 3 can be applied for computing FS for any combination of random and design parameters.

Quantifying the Failure Probability of the System

In the probabilistic design approach, the failure probability or other concepts such as the reliability index is used as a measure of safety. This paper evaluates the failure probability using the Monte Carlo simulations (MCS) based on the response surface in Eq. 2. The simulation is deemed to be in the failure region if the calculated FS is less than the required FS of 1.5. The soil-related random variables (φ, s_u) were assumed to be normally distributed as φ= N (33,1.67) and s_u= N (31,3.67) to evaluate the effect of random variables on P_f computation. It should be noted that the flood water elevation varies from the crown of the levee (0 m) to the wall top (2 m) and the variation of failure probability was monitored with floodwater elevation as the loading-related random variable.

As shown in Figs. 11-13, the maximum water elevations with acceptable P_f were 2 m, 1.7 m and 1.3 m for cases D_{max}, D_{mid} and D_{min} (X and S at mid. value), respectively; 2 m, 1.8 m and 1.5 m for cases X_{max}, X_{mid} and X_{min} (D and S at mid. value); and 2 m, 1.7 m and 1.1 m for cases S_{min}, S_{mid} and S_{max} (D and X at mid. value), respectively.

Overall, it can be concluded from Figs. 11-13 that P_f of the I-walls and levee system decreases with increasing D, increasing X and decreasing S. Moreover, based on the allowable failure probability of 0.01 (Jonkman et al. 2009), the design combinations that satisfy this safety constraint are: (D_{max}, X_{mid}, S_{mid}), (D_{mid}, X_{max}, S_{mid}), (D_{mid}, X_{mid}, S_{min}). However, more design sets can be generated that meet the safety criteria by adjusting the design parameters. For example, although D_{min} in a design set causes the failure probability of the system exceeding the allowable one, the combination of D_{min} with X_{max} and S_{min} can result in satisfactory performance of the system.

5. DESIGN OPTIMIZATION FOR STABILITY OF I-WALLS AND LEVEE SYSTEM

Non-Robust Design Optimization Results

The design optimization was firstly performed to minimize both the cost and the failure probability using the multi-objective optimization procedures (Deb et al. 2002; Yu et al. 2019). The cost of I-walls and levee system is expressed as a function of the design parameters (D, X and S) based on the construction volume of each component and respective unit cost data by RSmeans (Waier et al. 2010; Rahbari and Ravichandran 2018). It should be noted that in this type of design optimization, robustness was not considered, and only cost and safety were considered as two design objectives. The failure probability is evaluated using Monte Carlo simulation with the total sample number $N = 5000$. As a safety constraint, an allowable P_f equal to 0.01 was assumed in the optimization setting. The resulted Pareto front shows a trade-off relationship between cost efficiency (minimizing the cost) and safety (minimizing the failure probability), which is depicted as a non-robust Pareto Front in Fig. 15.

Robust Design Optimization Results

Certainty in the computation of the failure probability of the system may be guaranteed by using high-quality data of the soil profile in the model. However, uncertainties exist in the assumed statistical characterization of soil properties due to insufficient sample size, measurement errors, and human errors and the computed failure probability will not be a certain value and vary under the effect of these variations (Rahbari 2017; Luo and Hu 2019; Wu and Luo 2020). Therefore, in this section, the coefficient of variations (COV) of the soil-related random variables (φ and s_u) were also considered as uncertain parameters in the optimization setting as COV_{φ} = N (0.05, 0.01), COV_{su}= N (0.12, 0.024).

For each design set, M number of P_f were calculated (note: M is the number of MCS runs to obtained the standard deviation of P_f). Considering P_f as the response of concern, the standard deviation of P_f was taken as the measure of robustness (Wang et al. 2015). The design optimization was performed by minimizing the cost and maximizing the robustness. Reducing the variation of response (standard deviation of the failure probability, here) leads to increasing the robustness of the design. The Pareto front optimized to cost and standard deviation of P_f is shown in Fig. 14 (for M =1000). It can be observed from the Fig. that as the standard deviation of P_f increased from 0 to about 0.0017, the cost decreased from $2800 to $1900. This indicates that higher robustness for design demands a higher cost.

Comparison of Robust and Non-Robust Design Optimization

In this section, the Pareto front resulted from robust design optimization is compared with the one resulted from non-robust design optimization, as shown in Fig. 15. The non-robust Pareto front is located below the robust Pareto front showing the lower cost of design when the robustness of the system is not considered. In other words, robust design optimization may lead to costlier designs than non-robust design, but reducing the sensitivity of the design and the variation of the response (failure probability) is the key to obtain designs of higher robustness.

Determination of Final Design

To identify the most preferred design on the Pareto front, the normal boundary intersection (NBI) (Das and Dennis, 1998) approach was used to compute the knee points on the robust Pareto front. As shown in Fig. 16, for each point of the Pareto front, the distance from the boundary line, which connects the highest point of the Pareto front to the lowest point, is computed in the normalized space of the Pareto front. Then, the point with maximum distance from the boundary line is sought and selected as the knee point which corresponds to the most preferred design of the study based on the gain-sacrifice relationship among the designs on the Pareto front.

The most preferred designs (*D*, *X*, *S*, and associated cost) extracted using the knee point characteristics of the robust and non-robust design Pareto fronts are summarized in Table 6. The most preferred robust design included a levee with a wide crown and mild slope for the levee landside and short wall. On the other hand, the most preferred non-robust design included a levee with a middle-value width for the crown. From the comparison study, a mild slope (about 4H:1V) for the levee landside is recommended for the final design of I-walls and levee system. The levee crown's increased width in the most preferred robust design increased the cost of the system. However, in the meantime, the robustness of the design also increased considerably. This higher cost for the robust design may seem unreasonable compared to conventional design, but the robust design helps to reduce the unexpected variations in the system response. The proposed robust design optimization framework will assist the designers to make a more informed decision by explicitly considering the safety, cost, and robustness.

6. CONCLUSION

A general framework for designing and optimizing I-walls and levees system resting on sandy foundation soil is proposed. The uncertainties associated with the geotechnical properties and loads from the flood water are systematically considered. The stability of I-walls and levee system was evaluated using finite element and limit equilibrium methods, and a response surface for the factor of safety was developed based on the computed results. Then, using the formulated response surface, the failure probability was determined using Monte Carlo simulations. A multi-objective design optimizations were conducted to derive the non-robust Pareto front (cost vs. failure probability) and robust Pareto front (cost vs. standard deviation of the failure probability). The robust design framework optimizes the robustness (in terms of minimizing the standard deviation of the failure probability) and cost-efficiency (in terms of minimizing the cost) simultaneously while satisfying the safety requirements. The robust design framework can be directly used to design I-walls and levees system resting on sandy soil for its stability to mitigate the risk of catastrophic failures caused by geotechnical and floodwater uncertainties.

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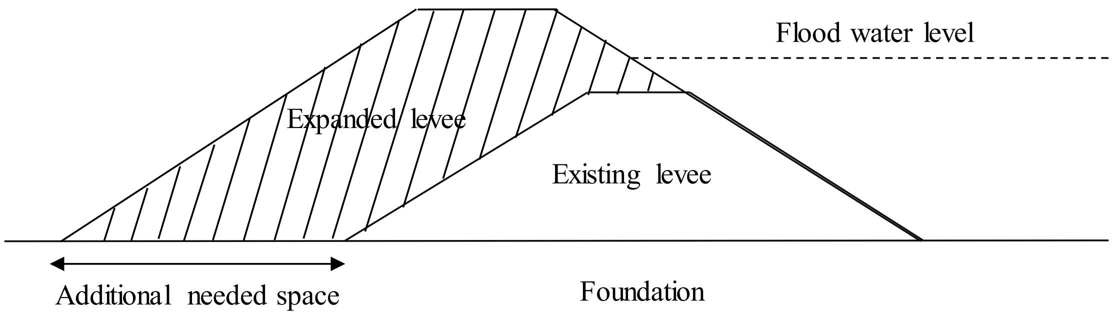


Figure 1 Expanding levee section

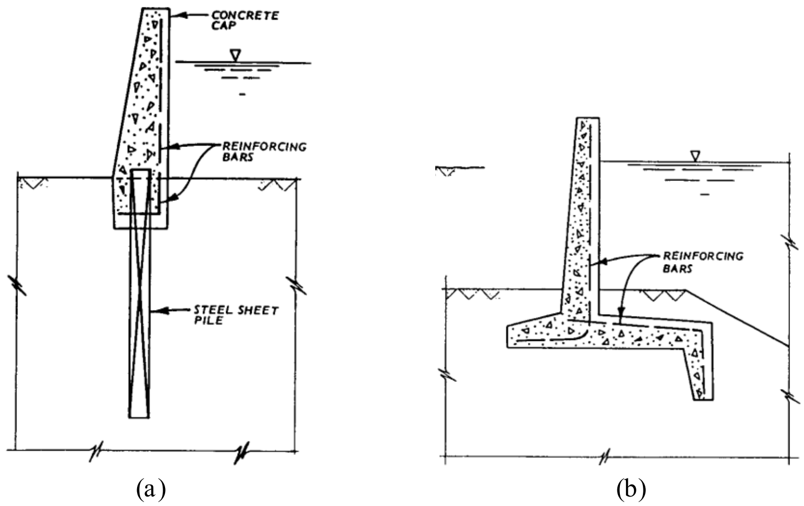
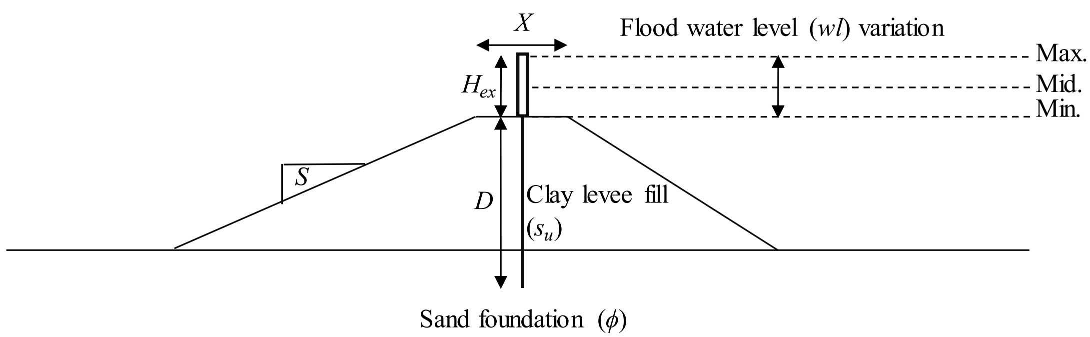


Figure 2 Common floodwalls: (a) I-walls and (b) T-walls (from USACE 2011)



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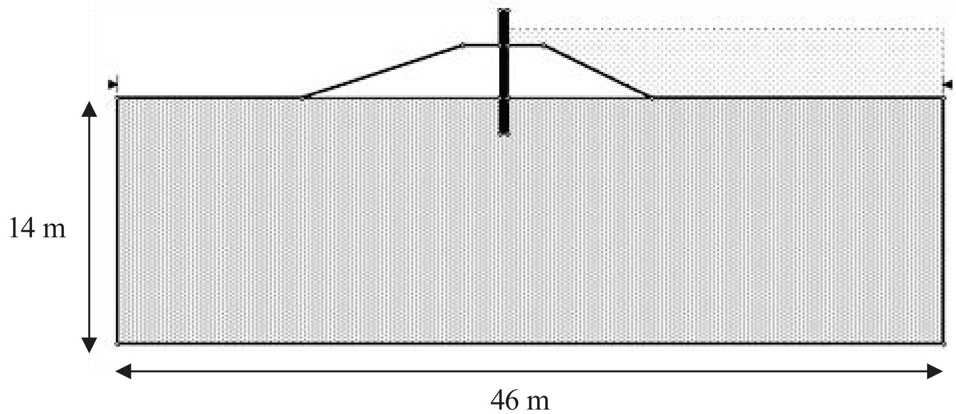

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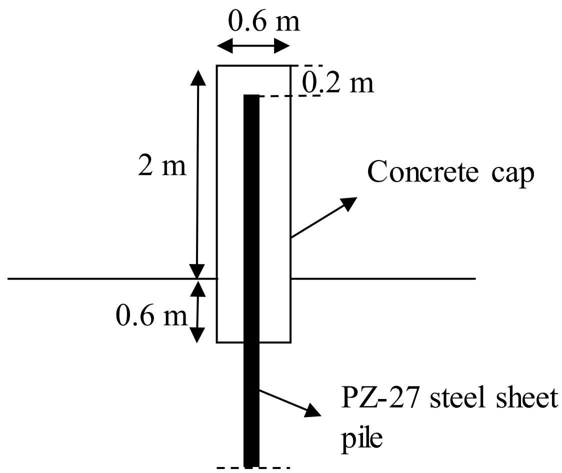

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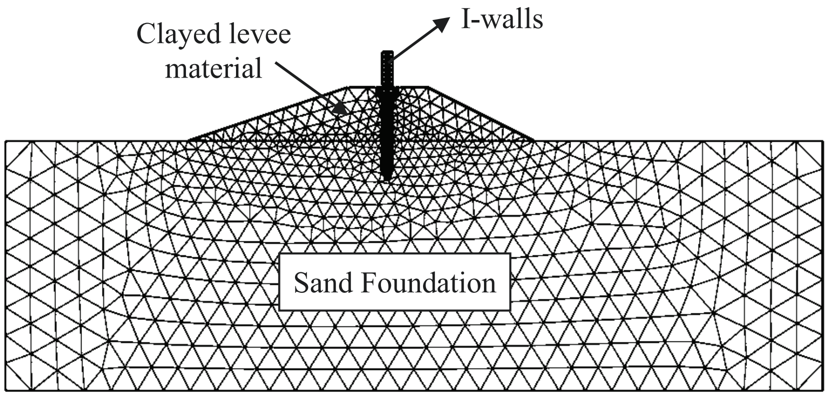

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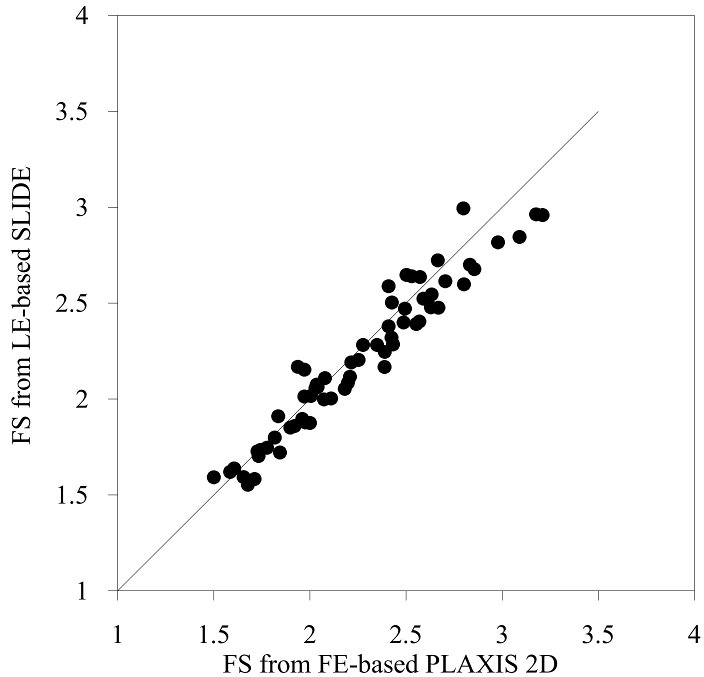

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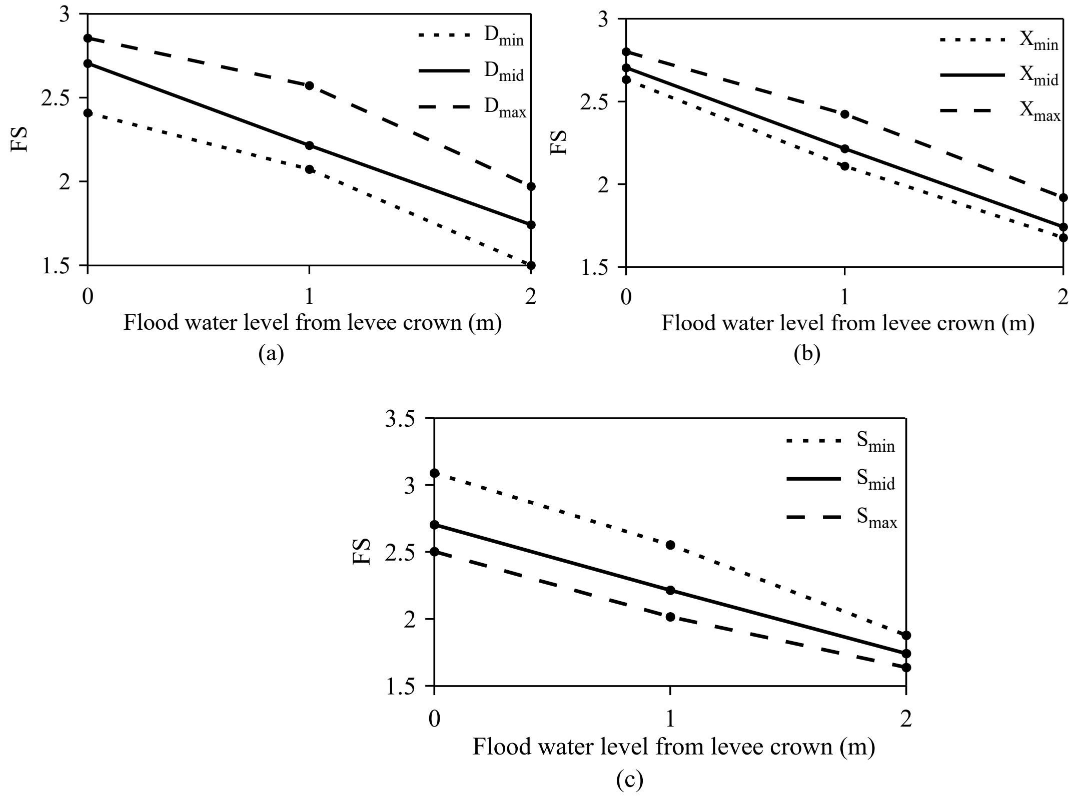
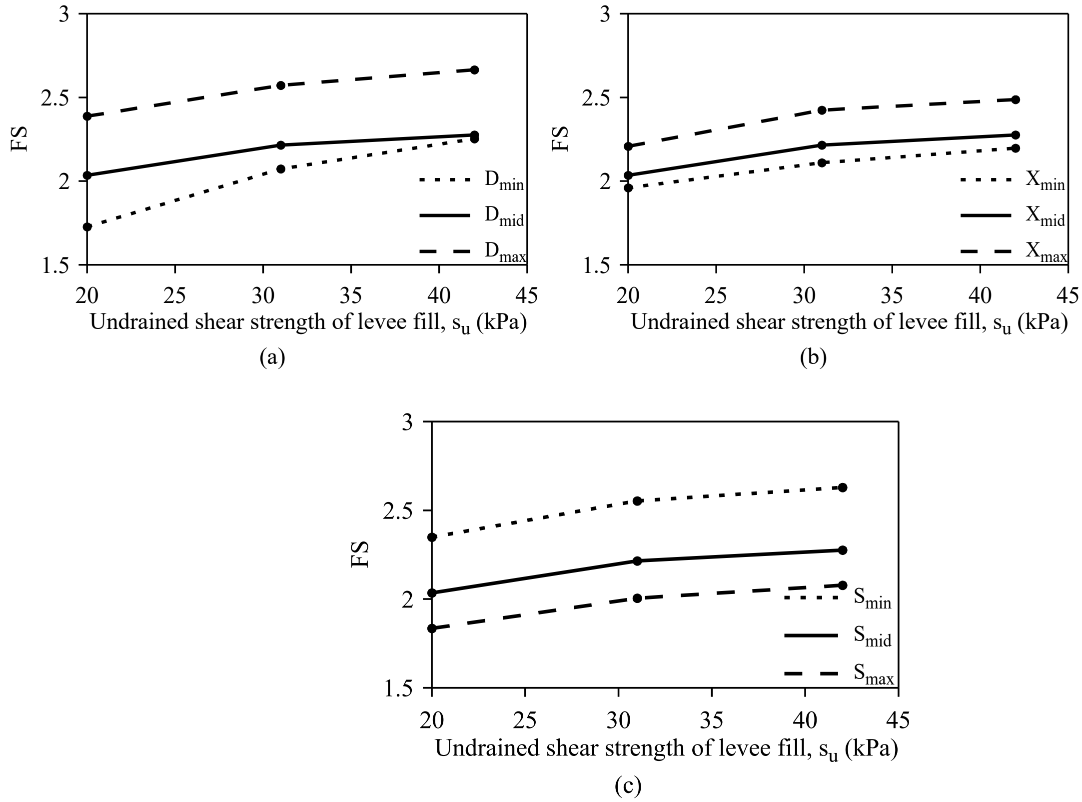


Figure 8 Variation of FS with flood water level (a: effects of embedded depth of wall *D*; b: effects of levee crown width *X*; c: effects of slope ratio of the landside *S*)



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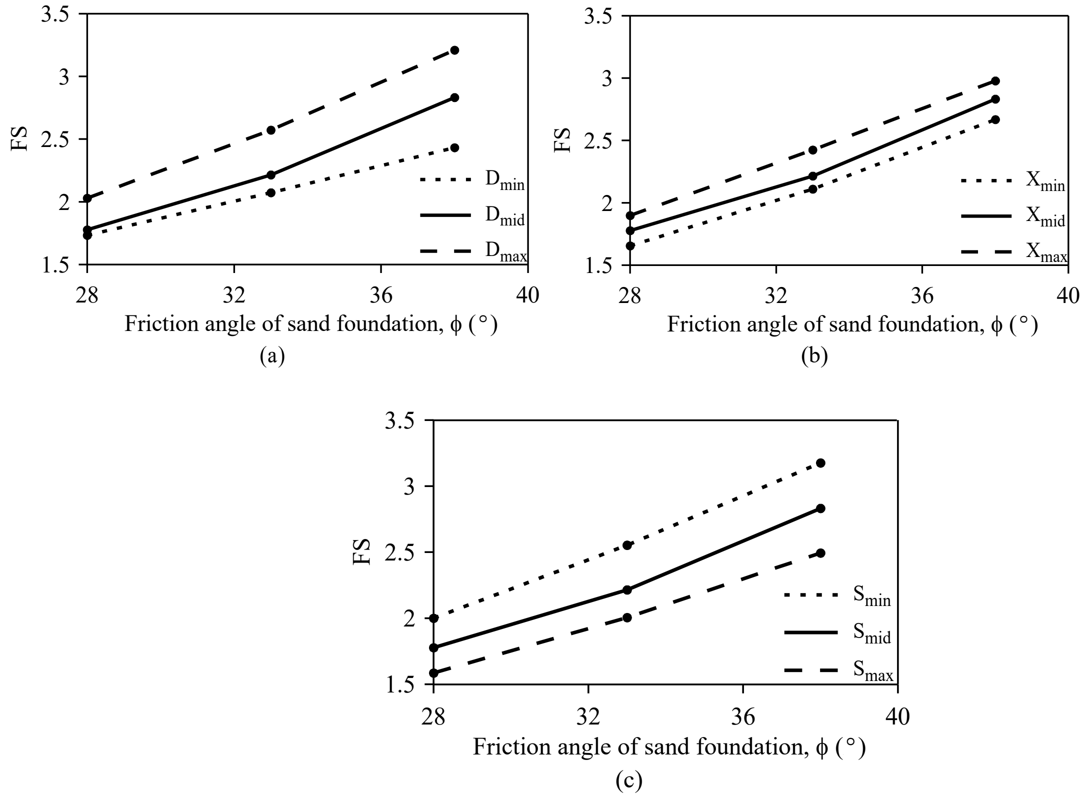

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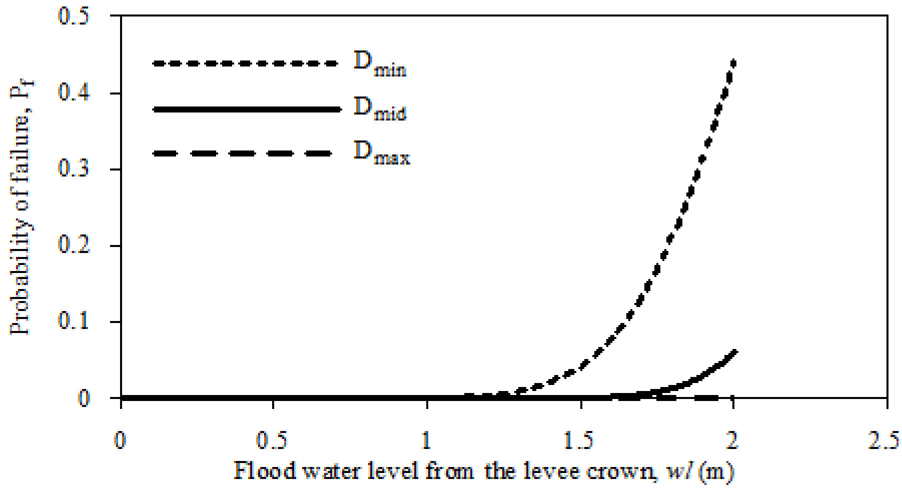

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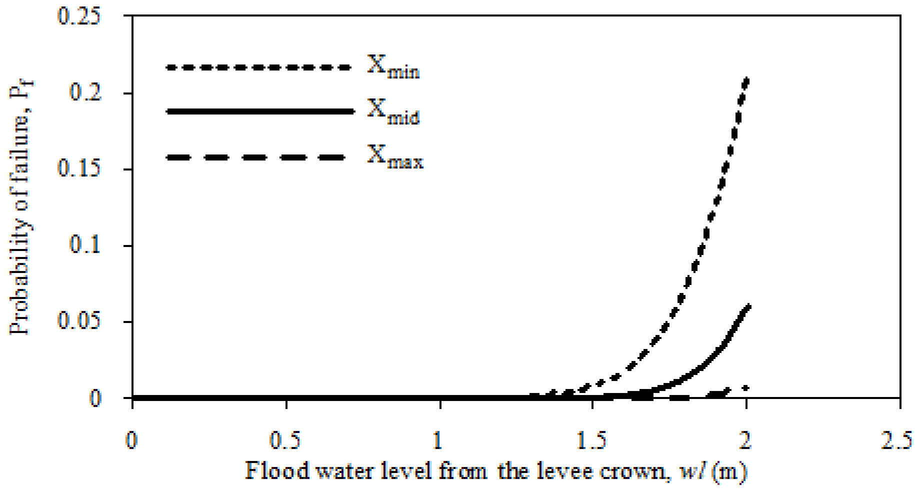

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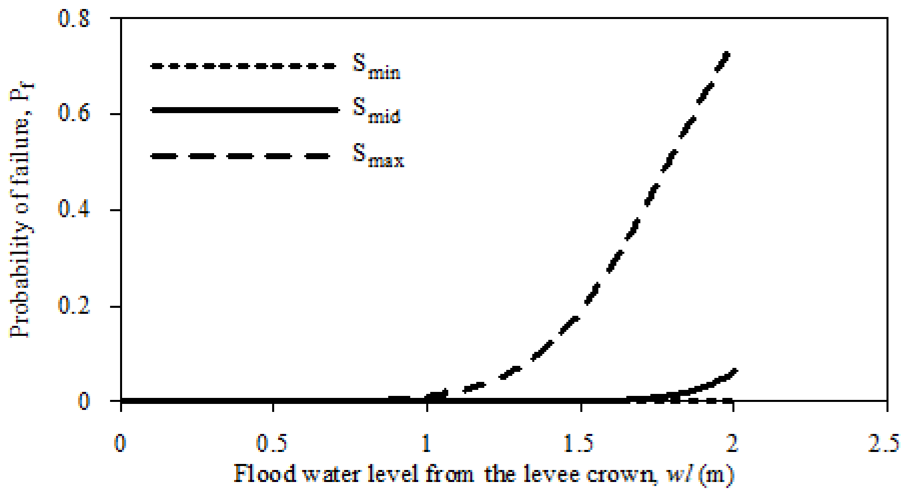

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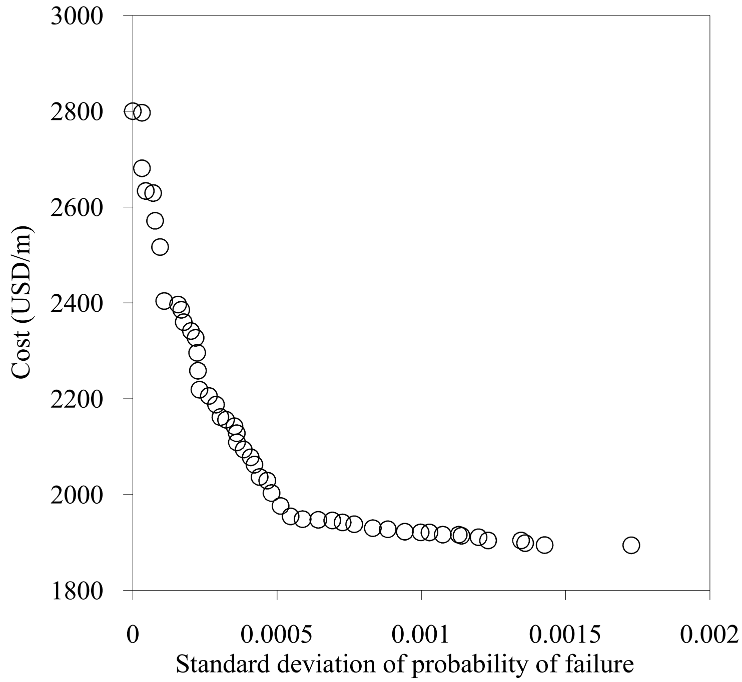

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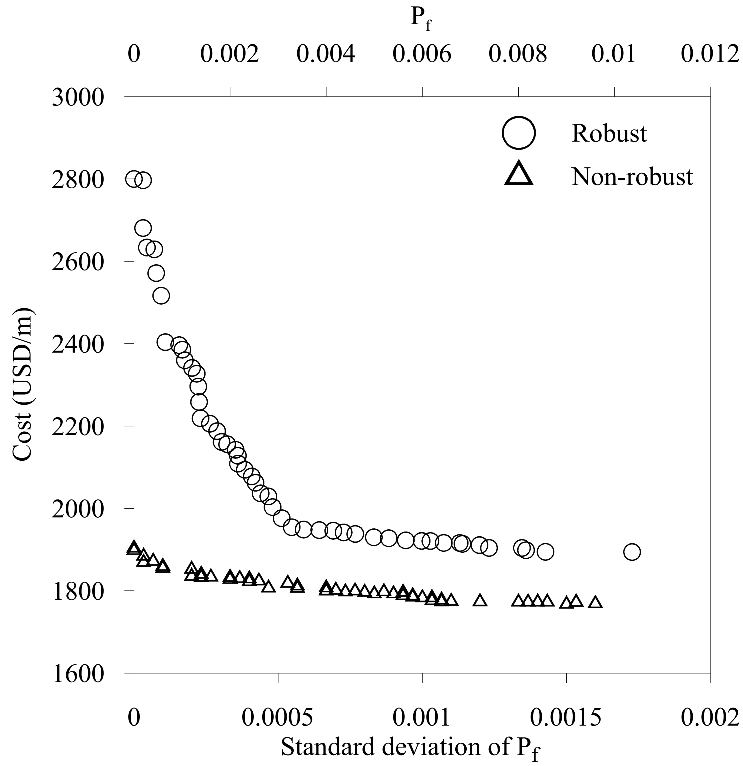

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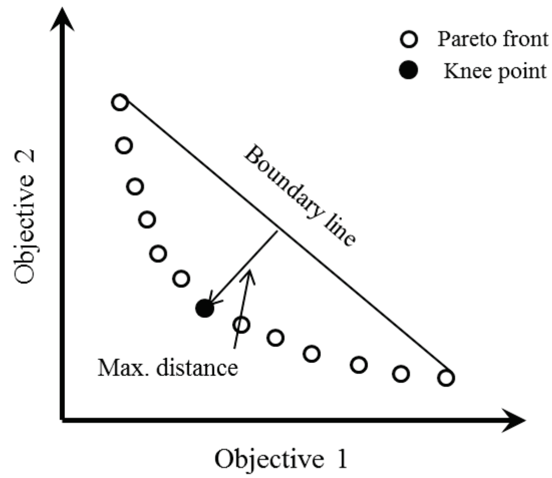

Figure 16 Normal boundary intersection approach

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Table 1 Design variables in the study

Design variable	Wall embedded depth, *D* (m)	Levee crown width, *X* (m)	Levee landside slope, *S*
Range	2-8	3-6	0.25-0.5

Table 2 Random variables and their statistical values

Random variable	Range	Mean value	Standard deviation
φ (°)	28-38	33	1.67
s_u (kPa)	20-42	31	3.67
wl (m)	0-2	1	-

Table 3 Material properties of the sheet pile wall using PZ-27

PZ-27	**Parameter**	**Unit**	**Value**
From Bethlehem steel corporation	h	mm	305
	A	cm^2/m	168.1
	weight	kg/m^2	131.8
	I	cm^4/m	25200
Used in PLAXIS 2D	$EA\ (= E(hb))$	kN/m	3.362×10^6
	$EI\ \left(= E\left(\frac{bh^3}{12}\right)\right)$	$kN.m^2/m$	5.04×10^4
	$d\ \left(= h = \sqrt{12\left(\frac{I}{A}\right)}\right)$	m	0.4241
	$w\ (= weight \times g \times 10^{-3})$	kN/m/m	1.293

Table 4 Selected design combinations for parametric study

Combination	***D*** **(m)**	***X*** **(m)**	***S***
D_{mid}, X_{mid}, S_{mid}	5	4.5	0.33
D_{min}, X_{min}, S_{min}	2	3	0.25
D_{max}, X_{max}, S_{max}	8	6	0.5
$\boldsymbol{D_{min}}$, X_{mid}, S_{mid}	2	4.5	0.33
$\boldsymbol{D_{max}}$, X_{mid}, S_{mid}	8	4.5	0.33
D_{mid}, $\boldsymbol{X_{min}}$, S_{mid}	5	3	0.33
D_{mid}, $\boldsymbol{X_{max}}$, S_{mid}	5	6	0.33
D_{mid}, X_{mid}, $\boldsymbol{S_{min}}$	5	4.5	0.25
D_{mid}, X_{mid}, $\boldsymbol{S_{max}}$	5	4.5	0.5

Table 5 Performance ratings for recommended statistics (after Moriasi et al. 2007)

Performance rating	RSR	NSE	PBIAS
Very Good	0-0.5	0.75-1	<±15
Good	0.5-0.6	0.65-0.75	±15 - ±30
Satisfactory	0.6-0.7	0.5-0.65	±30 - ±55
Unsatisfactory	>0.7	<0.5	> ±55
Response surface rating	0.24	0.94	-0.36

Table 6 Design parameters of the most preferred design for robust and non-robust optimization

Optimization type	D (m)	X (m)	S	Cost (USD/m)
Robust	2.00	6.00	0.25	1954
Non-robust	2.00	3.55	0.28	1807