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Effect of Statistical Data in the Probabilistic Analysis for Port-Said East Port Diaphragm Quay Wall

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ABSTRACT

Quay walls and deep excavations are typical applications of geotechnical retaining structures. These structures must be acceptable safe, and cost-effective. The design of retaining structures is usually carried out by using characteristic values for soil properties as a conservative estimation for Serviceability Limit State (SLS) and combined with safety factors for Ultimate Limit State (ULS). The soil parameters used in the design are uncertain values due to many reasons. Recently, probabilistic approaches started to take place in the engineering community. These approaches guaranty a reasonable level of reliability and reduces the risk and the investment cost. In the present paper, a developed technique for coupling between PLAXIS 2D V20 and Probabilistic Tool-Kit (PTK) will be employed to perform a reliability analysis for port-said east port diaphragm quay wall. This study aims to identify the probability of failure and the importance factors for each structural component using the First Order Reliability Method (FORM) and study the effect of varying the statistical data for the most significant soil parameters. The results show that the developed technique can perform the reliability analysis effectively. Also, it showed that the statistical data for soil parameters have a considerable effect on the probabilistic analysis results.

Keywords: Soil structure interaction, Reliability analysis, Coupling technique, PTK, FORM, Uncertainty.

1.INTRODUCTION

The Finite Element Method (FEM) is used to accurately determine the response of a complex structure subjected to specific loads. The finite element provides an accurate result when it is properly modelled. FEM has proved to be one of the most effective approaches in developing an analytical formulation of a complex problem. On the other hand, the uncertainties in the input parameters, mainly the soil parameters, are rather significant, particularly in geotechnical engineering. As a result, using probabilistic approaches is attractive.

According to Baecher and Christian 2003 [1], there are three types of uncertainty in geotechnical engineering which can be summarized as:

- Aleatoric uncertainty.
- Epistemic uncertainty.
- Decision uncertainty.

The first type of uncertainty is related to the random changes in the soil composition. This uncertainty can be defined by changes of the soil properties with time at a specific location, temporal variability, or over space at a single time, spatial variability.

The second type of uncertainty is divided into site specification, model uncertainty, and parameter uncertainty. These uncertainties are caused by deficits in knowledge about the phenomenon or the material rules, which prevents creation of a practical model. Lastly, the third type of uncertainty refers to the challenge of being observant of public goals, identifying general principles like planning estimation.

Conventional design approaches use safety factors which are usually based on simple models and limited probabilistic calculations. These safety factors are coupled with several conservative assumptions to carry out the structural design. As a result, the full probabilistic analysis for assessing the reliability is the basis for developing an appropriate design and evaluation tools to handle the various types of uncertainties. CUR-publication 190, 1997 [2].

In the reliability analysis, each parameter regarded as a random variable must be expressed by statistical data calculated using engineering judgment or field tests. Multiple alternative statistical data can fit data collection; their suitability for geotechnical parameters is still under development.

The method of describing the random variable using specific statistical distribution is called "single random variable," which is valid when the soil is considered homogeneous. On the other hand, a practical model should account for the spatial correlation in areas where the stochastic properties can differ. Fenton and Vanmarcke 1990 [3] developed the Random Finite Element Method (RFEM) for this purpose, in which stochastic parameters are compared together using the auto-correlation methods.

The combination between finite element and reliability techniques has the later benefits according to Waarts 2000 [4]:

- It provides a clear insight into structural reliability and critical parameters instead of traditional finite element analysis.
- The Systems created using finite element coupling techniques would be safer or more economically than those created using safety factors and traditional methods.

There are some studies in the literature which carried out a reliability analysis for different types of structures. Abdel-Fattah 2017 [5] presented a reliability-based analysis for slope stability problem since it is a representative application for calibrating the soil strength parameters. Ashraf et al., 2020 [6] employed a robust and accurate method called Monte Carlo Simulation (MCS) in a probabilistic analysis of a strip footing resting on a clayey soil with uncertain soil properties. Larsson, 2015 [7] examined the distinctions and relationships between the various levels of reliability methods.

Limited studies for the reliability analysis for complex structures were carried out. Some of these studies are: Schweckendiek 2006 [8] presented a reliability analysis which accounts for the uncertainties in the soil parameters and the groundwater levels and the strength reduction of the structural components due to corrosion. Teixeira and Rippi 2016 [9] presented the benefits of a reliability-based analysis and employed the open-source open turns tool for the reliability study, combined with a finite element tool for limit state evaluation. Brinkman and Post 2019 [10] studied the reliability-based analysis for sheet pile retaining structures using finite element program PLAXIS. Wolters 2012 [11] contributed to the development of sheet-pile structures concerning quay wall design via a PLAXIS-FORM coupling using prob2b reliability library. Teixeira et al., 2015 [12] aims to create a "FEM – probabilistic library" connection that is "simple to use" and suitable to a wide range of soil-structure interaction situations. Ene et al., 2021 [13] used a different probability distribution for assessing the statistics of the geotechnical parameters and examines the necessity of including more specific target reliability values for SLS verification and especially for temporary structures in the design codes.

In this paper, a developed technique for coupling between PLAXIS 2D V20 and Probabilistic tool-kit (PTK) from deltares, will be employed to perform a reliability analysis for port-said east port diaphragm quay wall.

The First Order Reliability Method (FORM) will be used to calculate the probability of failure, the reliability index, and the important factors for the structural components and the system as a whole. The effect of using a different probability distribution with different coefficients of variation for the most important soil parameters will also be studied. The results of this paper may be helpful in decision-making for the assessment of an existing structure.

2.RELIABILITY METHODS

2.1 Reliability Analysis Principals.

Determination of failure probability is the most crucial factor in determining an element's reliability. The limit state is the boundary between failure and non-failure. In contrast, the possibility that this threshold will not be exceeded is known as reliability. Limit State Functions (LSF) are used to interpret limit states, and their typical form (Baecher and Christian 2003 [1]) is:

$$Z = R - S \qquad (1)$$

Where (R) is the resistance or the component which contribute to non-failure. while (S) and sometimes (Q) is the load or the component which contribute to failure.

Resistance should be greater than load in structural design, or the performance function must be greater than zero (Z>0). The primary goal for the system is that this requirement remains relevant during the life time of the system. However, almost all of the parameters which forms resistance and load are uncertain. Therefore, the probability of non-failure for a given system is calculated and used to indicate the system reliability, P(Z>0). Probability of failure is:

$$Pf = P\ (Z \leq 0) = P\ (S \geq R) \qquad (2)$$

As a result, the reliability could be in the sense that:

$$P (Z > 0) = 1 - Pf \qquad (3)$$

Figure 1 shows the safe domain, failure domain and the LSF corresponds to R-S = 0 according to Chandrasekaran 2016 [14].

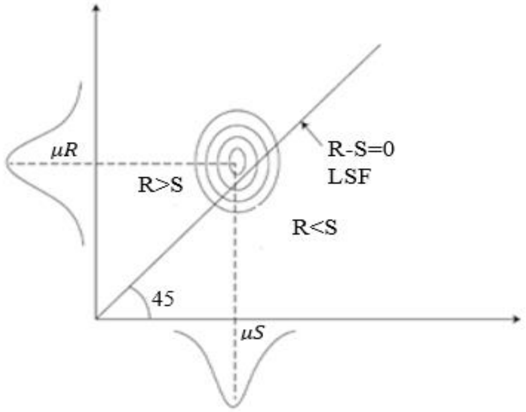


Figure 1: Safe domain and failure domain

The design concept is based on one of the most crucial fundamentals, called design point, which is located on the limit state surface and has the shortest distance to the mean values of random variables. The design point is where the joint Probability Density Function (PDF) of random variables intersects with the limit state surface, indicating the most probable point of failure. Figure 2 shows the design point in the space of random variables.

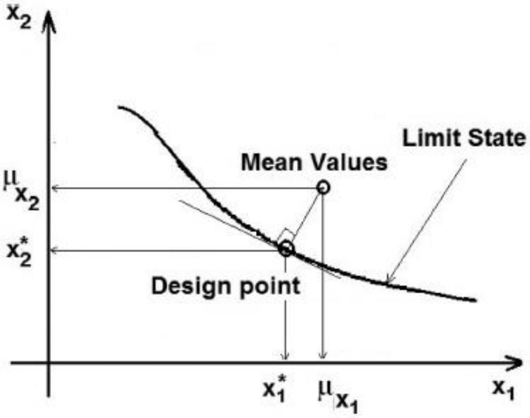


Figure 2: Design point in the space of random variables.

2.2 First Order Reliability Method (FORM)

First Order Reliability Method (FORM) is considered a level II method. The principal of this method is to linearize the LSF in U-space. Its accuracy decreases as the LSF becomes more non-linear in the areas of large probability density. FORM has significant deffect in which it cannot deal with numerous LSF. As a result, FORM should only be employed when there are no consedrables impact on outputs due to non-linearities or system effects. Figure 3 shows the linearization of the LSF carried out on the point in which (Z = 0), which is called the design point.

The stochastic parameters are converted into typical standard normally distributed parameters and the overall process is done in U-space. According to Hasofer and Lind 1974 [15], for parameters with a normal distribution the conversion process may be expressed as shown:

$$ui = \frac{x_i - \mu_{xi}}{\sigma_{xi}} \qquad (4)$$

where; (ui) is the normalized variable, (x_i) is the variable value in x space, (μ_{xi}) is the normalized mean and (σ_{xi}) is the normalized standard deviation.

The FORM algorithms need derivatives of the limit state function concerning xi to be determined. Aiming this, the following relationship can be used:

$$dxi / dui = \sigma_{xi} \qquad (5)$$

$$\frac{\partial Z}{\partial ui} = \frac{\partial Z}{\partial xi} \cdot \frac{\partial xi}{\partial ui} = \frac{\partial Z}{\partial xi} \cdot \sigma_{xi} \qquad (6)$$

The limit state function, only expressed in terms of resistance and load becomes:

$$Z = R - S = \sigma_R U_R - \sigma_S U_S + \mu_R - \mu_S = 0 \qquad (7)$$

To determine the reliability index β and probability of failure Pf, this distance must be minimized. A Lagrangian Multiplier Approach or a Tylor Series Approach might be used to elaborate on this minimization problem. Both of these approaches lead to the same solution.

$$\beta = \frac{\mu_Z}{\sigma_Z} = - \frac{\sum u_i (\frac{\partial Z}{\partial u_i})}{\sqrt{\sum (\frac{\partial Z}{\partial x_i})^2}} \qquad (8)$$

Then the term influence factors may be defined as follows:

$$\alpha_i = \frac{(\frac{\partial Z}{\partial u_i})}{\sqrt{\sum (\frac{\partial Z}{\partial x_i})^2}} \qquad (9)$$

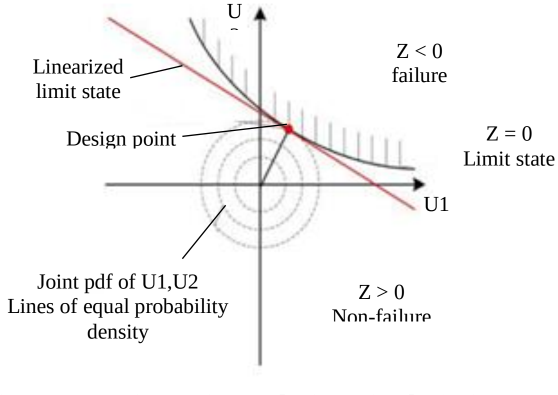


Figure 3: Design Point and Linearized Limit State in case of FORM.

3.COUPLING RELIABILTY ANALYSIS WITH FEM

The limit state evaluation for complex systems requires a finite element program such as PLAXIS. While the reliability analysis requires a probabilistic library to deal with the reliability methods, such as the Probabilistic Tool-Kit (PTK).

A communication interface is required for coupling the PTK with PLAXIS. The interface should modify PLAXIS inputs and read PLAXIS outputs. According to the chosen reliability analysis approach, PLAXIS must read the new values that PTK simulates for the selected random variables during the iterative process.

In principle to run a reliability analysis using PTK, the following steps must be performed:

- Choosing the preferable reliability method.
- Defining the input random variables and their probability distributions.
- Defining the correlation matrix if any.
- Set the limit state function according to situation.

According to the probabilistic run in the PTK, PTK will calculate a new value for the chosen random variables, and now they are ready to be sent to PLAXIS. For this transmission, a python script (input interpreter) is required to send this input data to PLAXIS and perform the PLAXIS calculations. After the PLAXIS calculation is finished, a python script (output interpreter) extracts the desired results and sends them back to the PTK. PTK evaluates the new outcomes and prepares a new PLAXIS simulation to be sent again to PLAXIS. This loop will continue until specific convergence requirements are reached; at this point, the loop will be terminated. Figure 4 shows the flow chart for the developed coupling between the PTK and PLAXIS 2D V20.

4. THE CASE STUDY AND THE USED RANDOM VARIABLES

The case study is located in Port Said east port; the study area includes a container terminal in which the quay wall is diaphragm wall type. A typical cross-section of the diaphragm quay wall structure is shown in Figure 5. The quay wall deck having dimensions of 1200 m length and 35 m width is carried on four barrettes having the cross-section of 3x1 m, the length of the barrettes is about 62.5m; the barrettes are connected in the transverse direction by 3x0.8 m top beams. The Spacing between the supporting system formed from the barrettes and the top beam is 7 m in the perpendicular direction. In the perpendicular direction, front and rear beams are used to support the crane and bollard loads.

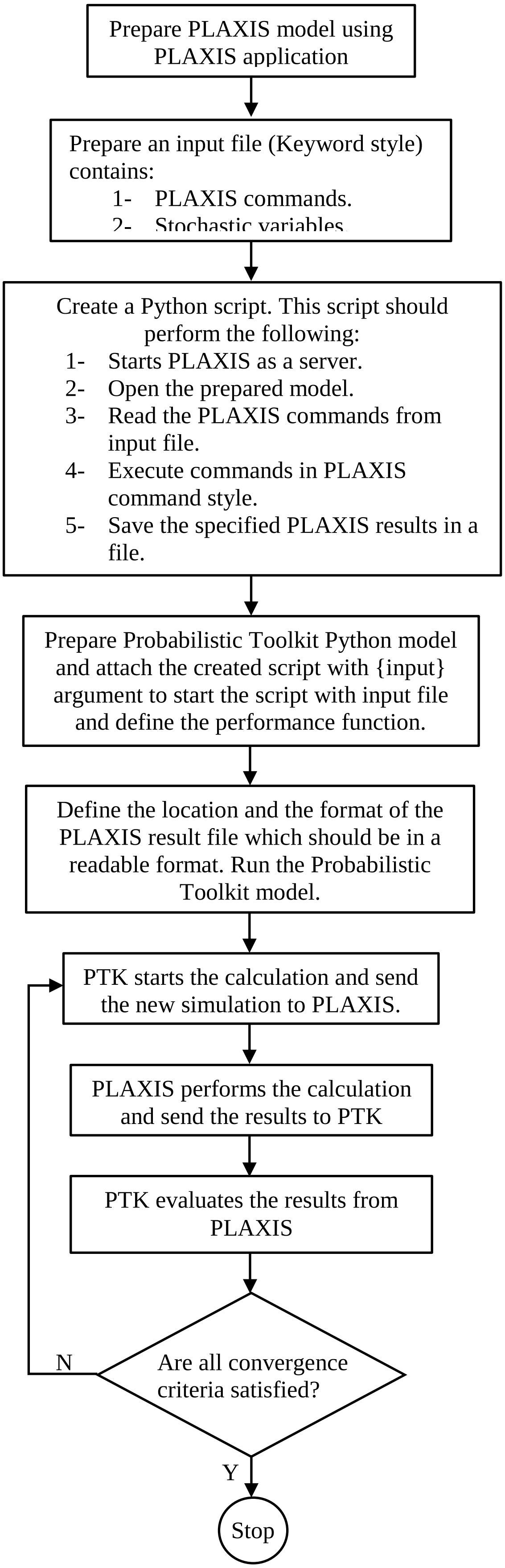


Figure 4: Flow chart of the coupling algorithm.

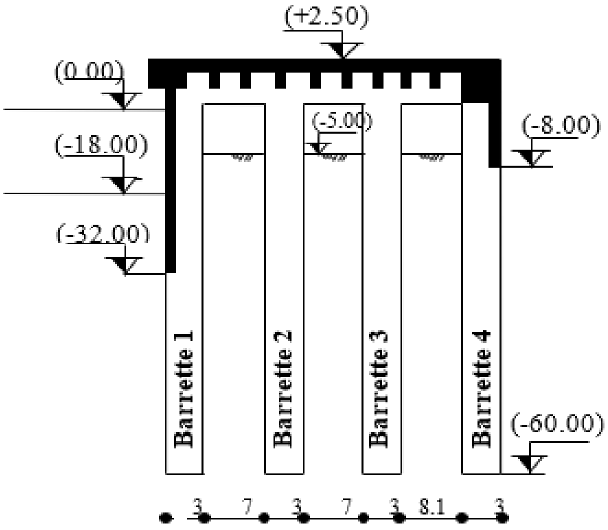


Figure 5 Diaphragm quay wall cross section.

The beam alignments of the Quay wall are shown in Figure 6.

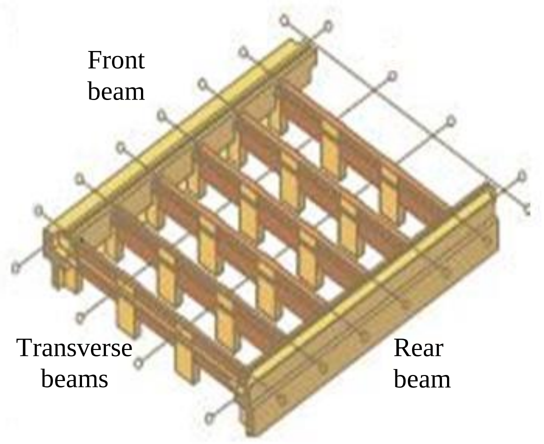


Figure 6 Diaphragm quay wall beam alignments.

4.1 Geotechnical Data

The available geotechnical data for the case study resulted from various soil samples taken from the site by the Norwegian Geotechnical Institute. Which performs a specific testing program for the soil samples, and the resulting elastic and plastic soil parameters for the different soil layers are listed in Table 1. The seawater level is taken at an elevation of 0.0. Hamza and Hamed 2000 [16].

Table 1: Geotechnical parameters.

Type	Thick (m)	γ_b KN/m^3	C` Kpa	Φ` Deg	C_u Kpa	G Mpa
Clay(A)	5	17	0	24	-	1
Sand(B)	8.5	18.5	0	35	-	12
Clay(D)	15	15.5	0	24	1*	2*
Clay(E)	30	15	0	20	1*	2*
Clay(G)	34	17.5	20	20	150	25
Sand(F)	Inf.	20	0	35	-	60

1* Soil strength varies linearly with depth Cu =20 + 1.24 z (kPa), from -11.0 to -56.0.
2* the shear modulus varies linearly with depth G= 5.6 + 0.14 z (Mpa), from -11.0 to -56.

Coefficients of variation and distributions types for soil characteristics were chosen based on the acquired knowledge about the possible ranges of such parameters. And also, according to the values given from the following researches (Baecher and Christian 2003 [1] and Wolters 2012 [11]). The statistical data including distribution types and coefficient of variation for the stochastic parameters are listed in Table 2.

Table 2: Statistical data for soil.

Soil Parameter	Distribution	COV
γ_{unsat} [kN/m^3]	Normal	5%
γ_{sat} [kN/m^3]	$\gamma_{unsat} + U(0.2)$	5%
C [kN/m^2]	Lognormal	25%
φ	Truncated Normal (0,45)	10%
E [kpa]	Lognormal	25%
υ [-]	Truncated Normal (0,0.5)	10%
$R_{int.}$ [-]	Truncated Normal (0,0.99)	20%

4.2 Loads

For the first design of the Quay wall, the following types of loads were taken into consideration. These types of loads are listed in Table.3. According to Hamza and Hamed 2000 [16].

Table 3: Types of loads for port said east port.

Type of load	Value
Berthing loads	100 kN/m’
Mooring loads	100 kN/m’
Crane load	Vertical crane load = 800 kN/m’ Horizontal crane load = 80 kN/m’
Surcharge loads	deck of the quay wall = 60 kN/m^2 road behind quay = 20 kN/m^2 area behind the road = 60 kN/m^2

The elastoplastic Mohr-Coulomb model will be used to simulate the soil behavior as it is sufficiently accurate instead of the Hardening soil model that gives some randomness in the results, which conflict with the convergence criteria of the reliability methods such as FORM. Figure 7 shows the finite element mesh of the case study.

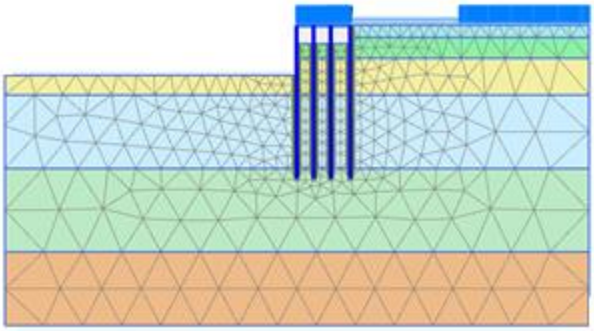


Figure 7 The finite element mesh of the case study.

5. PERFORMANCE AND LIMIT STATE FUNCTIONS.

Definition for various failure mechanisms is required to carry out a reliability analysis for any structure. The ultimate limit state (ULS) of failure is the focus of this study. For a diaphragm quay wall, there are mainly five types of structural elements:

- Barrette No. (1) from sea side.
- Barrette No. (2) from sea side.
- Barrette No. (3) from sea side.
- Barrette No. (4) from sea side.
- Soil structure.

5.1 Barrettes Ultimate Limit State.

One of the most crucial failure mechanisms for the barrette is exceeding the allowable strength. The bending moments and axial forces are the main causes of the structure's response (shear forces can be neglected). The normal force affects the moment resistance. Thus, one should consider this effect. The limit state function LSF for the barrette section may be calculated as the difference between the maximum produced stress and the allowable strength, as illustrated in equation 10.

$$Z = \sigma_{all} - \sigma = \sigma_{all} - max(\frac{M(z)}{W} + \frac{N(z)}{A}) \qquad (10)$$

Where M(z) is the maximum bending moment excreted on the barrette [kN.m/m], N(z) corresponding axial force [kN/m], W is the elastic section modulus [m^3], A is the cross-sectional area of the barrette [m^2] and σ_{all} is the allowable stress for the barrette material.

5.2 Ultimate Limit State for Soil Failure

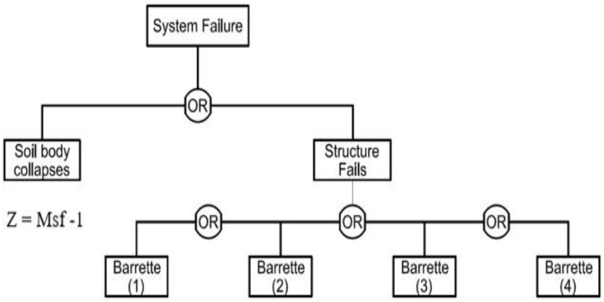
Safety calculation in PLAXIS may be helpful in computing the global safety factor. This calculation type could be helpful in the reliability analysis. The LSF for this approach could be formulated as follows:

$$Z = Msf - 1 \qquad (11)$$

Where Msf is the safety factor multiplier calculated from the safety calculation (Phi-C reduction) in PLAXIS. The failure occurs when the safety factor is less than one, this approach gives the general probability of failure for soil collapse.

5.3 Ultimate Limit State for System Failure.

After defining the LSF for the various elements for the case study, the fault tree for the overall system can be shown in Figure 8. The limit state function for the overall system may be considered as the first failure to occur from the five limit state functions which was mentioned before for the four barrettes and the soil.



$$Z = \sigma_{all} - \sigma = \sigma_{all} - \max(\frac{M(z)}{W} + \frac{N(z)}{A})$$

Figure 8 Fault tree and LSF for the case study.

6. RELIABILITY ANALYSIS RESULTS

Before carrying out the reliability analysis, it is necessary to conduct a Sensitivity Analysis (SA) to have a sense of the most influential variables and thus select the most important random variables to be used in the reliability analysis. The sensitivity analysis is also essential to minimize the computational efforts by reducing the number of variables considered stochastic parameters. The steps of the reliability analysis procedures are shown in Figure 9.

Table 4 lists the soil parameters that were regarded as stochastic in each LSF. These parameters were chosen based on SA and the engineering judgment.

Table 4: Stochastic variables for each LSF.

		Bar. (1)	Bar. (2)	Bar. (3)	Bar. (4)	Soil	System
Clay a	γ_{unsat}	✓	✓	✓	✓	✓	✓
	E		✓	✓	✓	✓	✓
	ν						
	C						
	R_{int}						
Sand b	γ_{unsat}	✓	✓	✓	✓	✓	✓
	E	✓	✓	✓	✓	✓	✓
	ν	✓	✓		✓		
	φ	✓	✓	✓	✓	✓	✓
	R_{int}	✓	✓		✓	✓	
Clay d	γ_{unsat}	✓		✓	✓	✓	✓
	E	✓	✓	✓	✓		
	ν	✓	✓		✓		
	C						
	R_{int}	✓	✓	✓	✓	✓	✓
Clay e	γ_{unsat}					✓	✓
	E	✓	✓	✓	✓		
	ν	✓	✓	✓	✓		
	C						
	R_{int}	✓	✓	✓	✓	✓	✓
Clay g	γ_{unsat}						
	E	✓	✓	✓	✓		
	ν						
	C					✓	✓
	R_{int}	✓	✓	✓	✓	✓	
Sand f	γ_{unsat}						
	E	✓	✓	✓	✓		
	ν					✓	
	C						
	R_{int}						

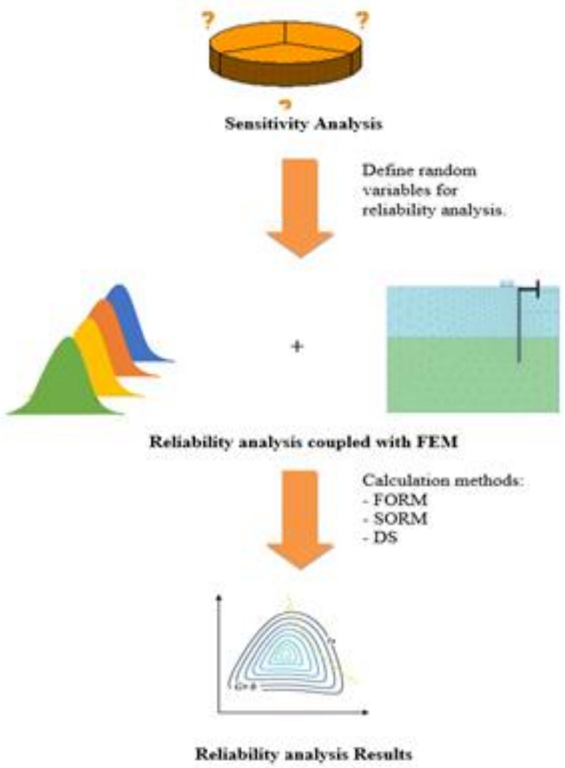


Figure 9 Steps of the reliability analysis procedures.

To study the effect of statistical soil parameters data on the reliability analysis results. Complete reliability analysis for the diaphragm quay wall with the statistical data listed in table 2 was carried out to compare its results with the results of the modified statistical parameters. The following section illustrates the results of the reliability analysis using Table 4 parameters.

6.1 Analysis of Barrette No. (1).

FORM is the reliability method employed in this analysis. The stochastic parameters that will be employed in the study were chosen based on sensitivity analysis findings and engineering judgment, as shown in Table 4. Table 5 lists the results of reliability analysis using the FORM method.

Table 5: FORM results for barrette No. (1) failure.

FORM Pf	$0.8*10^{-3}$
β	3.16
Number of models run	323
Iterations Max. No.	100
Analysis period (hr.)	3

Figure 10 shows the FORM importance factors for the barrette No. (1) failure. The figure shows that the limit state is mainly influenced by the angle of friction for the clay d layer and modulus of elasticity for the clay e layer. Also, the unit weight of the sand b layer seems to be important. The interface of the clay d layer appears to play a substantial role in barrette No. (1) allowable stress exceedance. It may be inferred that barrette No. (1) failure reached the plastic domain of soil as the strength property (φ) is important factor.

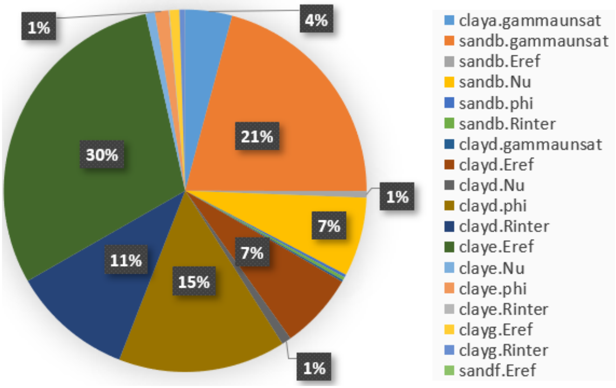


Figure 10 Importance factors α2 for Barrette No. (1) failure (FORM).

Figure 11 shows an illustration for deformed shape for design point as it resulted from the reliability analysis. From the figure, it may be concluded that due to the settlement behind the structure, the horizontal movement of the system increased, and barrette No. (1) is exposed to lateral pressure and subsequently reach its allowable stress. Also, the soil in front of the structure is influenced by a displacement in the up direction (heave) due to the rotational mode for the structure.

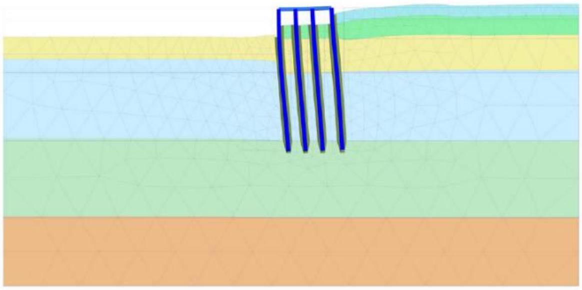


Figure 11 Deformed shape at design point for barrette No. (1) failure.

6.2 Analysis of Barrette No. (2).

FORM is the reliability method employed in this analysis. The stochastic parameters that will be employed in the study were chosen based on sensitivity analysis findings and engineering judgment, as shown in Table 4. Table 6 lists the results of reliability analysis using the FORM method.

Table 6: FORM results for barrette No. (2) failure.

FORM Pf	$3.67*10^{-5}$
β	3.97
Number of models runs	38
Iterations Max. No.	100
Analysis period (min.)	24

Figure 12 shows the FORM importance factors for barrette No. (2) failure. The figure shows that the limit state is mainly influenced by the angle of friction for the clay d layer and modulus of elasticity for the clay e layer. Also, the unit weight of the sand b layer seems to be important in barrette No. (2) allowable stress exceedance. It may be inferred that barrette No. (2) failure reached the plastic domain of soil as the strength property (φ) is an important factor.

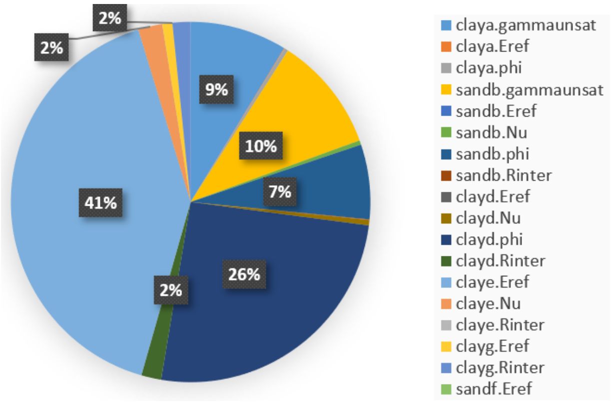


Figure 12 Importance factors α2 for Barrette No. (2) failure (FORM).

6.3 Analysis of Barrette No. (3).

FORM is the reliability method employed in this analysis. The stochastic parameters that will be employed in the study were chosen based on sensitivity analysis findings and engineering judgment, as shown in Table 4. Table 7 lists the results of reliability analysis using the FORM method.

Table 7: FORM results for barrette No. (3) failure.

FORM Pf	$24*10^{-4}$
β	2.98
Number of models runs	85
Iterations Max. No.	100
Analysis period (min.)	35

Figure 13 shows the FORM importance factors for barrette No. (3) failure. The figure shows that the limit state is mainly influenced by the angle of friction for the clay d layer and the modulus of elasticity for the clay e layer. It may be inferred that barrette No. (3) failure dose not reach the plastic region of soil as soil strength properties are not an important factor.

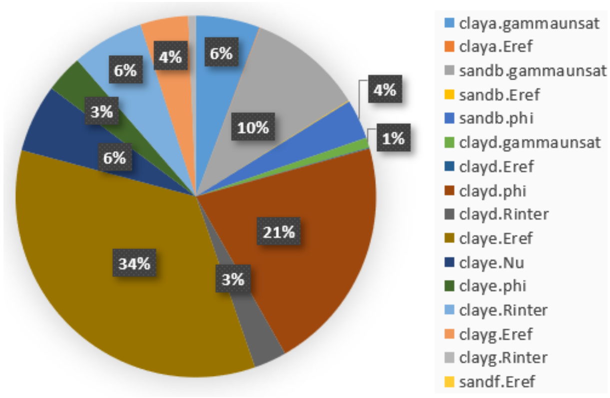


Figure 13 Importance factors α2 for Barrette No. (3) failure (FORM).

6.4 Analysis of Barrette No. (4).

FORM is the reliability method employed in this analysis. The stochastic parameters that will be employed in the study were chosen based on sensitivity analysis findings and engineering judgment, as shown in Table 4. Table 8 lists the results of reliability analysis using the FORM method.

Table 8: FORM results for barrette No. (4) failure.

FORM Pf	$3.8*10^{-4}$
β	3.67
Number of models runs	60
Iterations Max. No.	100
Analysis period (min.)	25

Figure 14 shows the FORM importance factors for barrette No. (4) failure. The figure shows that the limit state is mainly influenced by the modulus of elasticity for the clay e layer. Also, some properties significantly affect the LSF of barrette No. (4), such as the interface of clay e layer with importance factor 24% and the unit weight of sand b layer with importance factor 14%. It may be inferred that barrette No. (4) failure dose not reach the plastic region of soil as soil strength properties are not an important factor.

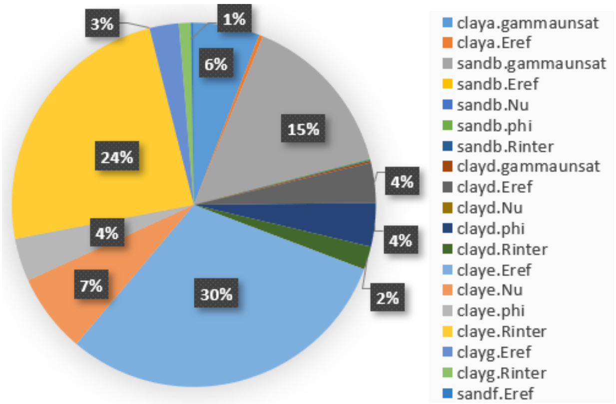


Figure 14 Importance factors α2 for Barrette No. (4) failure (FORM).

6.5 Soil Failure.

FORM is the reliability method employed in this analysis. The stochastic parameters that will be employed in the study were chosen based on sensitivity analysis findings and engineering judgment, as shown in Table 4. Table 9 lists the results of reliability analysis using the FORM method.

Table 9: FORM results for soil failure.

FORM Pf	$5.14*10^{-5}$
β	3.88
Number of models runs	1800
Iterations Max. No.	100
Analysis period (hr.)	11

Figure 15 shows the FORM importance factors for soil failure. The figure shows that the limit state is mainly influenced by the angle of friction for the clay e layer. Also, some properties significantly affect the LSF of soil, such as the interface of clay e layer with an importance factor of 25% and the interface of clay g layer with an importance factor of 17%. The soil reached its plastic domain as the strength property (friction angle for clay e layer) is important.

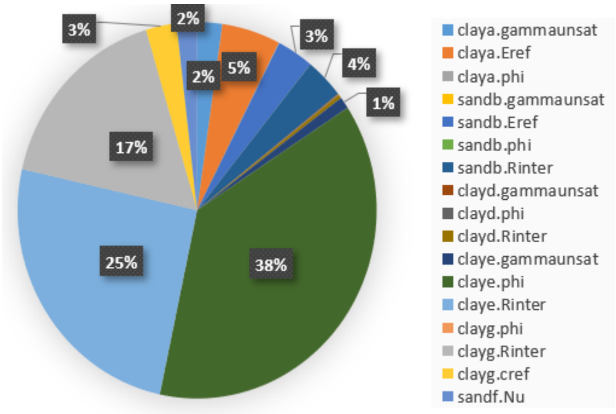


Figure 15 Importance factors α2 for soil failure (FORM).

6.6 Statistical data effect.

To verify the effect of the statistical data for soil parameters such as the coefficient of variation and the distribution type, for example, barrette No. (2) analysis will be made using a different COV and distribution type for the most critical soil parameters resulting from the previous reliability analysis (see section 6.2).

The COV for soil parameters represents the uncertainty. So, changing the COV value is expected to have a considerable effect on the reliability analysis results. From the reliability analysis for barrette No. (2), the most critical parameters that affects its failure were the angle of friction for clay d layer with an importance factor of 24% and the modulus of elasticity of clay e layer with an importance factor of 41%.

A parametric study will be carried out for different reasonably range values of COV and distribution types for the angle of friction for clay d layer and modulus of elasticity of clay e layer. Table 10 lists the parametric study properties.

Table 10: Parametric study properties.

Soil parameter	COV	Dist. Type
Angle of friction Clay d	5 – 15%	Normal (N)
Angle of friction Clay d	5 – 15%	Log-Normal (LN)
Modulus of elasticity Clay e	20 – 30%	Normal (N)
Modulus of elasticity Clay e	20 – 30%	Log-Normal (LN)

The parametric study results for the angle of internal friction for clay d layer are illustrated in Figure 16. From the figure, it is clear that considering the reliability index and probability of failure, the normal and log-normal distributions have the same trend with a slight difference in the values of reliability index, which are not greater than 4%.

The figure also shows that the increasing uncertainty level represented in COV leads to a considerable decrease in the reliability index by about 20%. It can also be concluded that within this reasonable range of COV (5-15%), the probability of failure increases by about 100%.

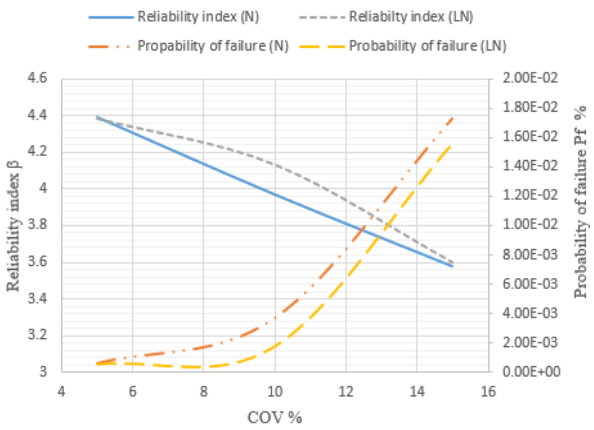


Figure 16 Reliability index and probability of failure for varying (∅) COV for two types of distributions.

The parametric study results for the elastic modulus for clay e layer are illustrated in Figure 17. It is clear that the normal and log-normal distributions, in this case, have more differences than the previous case. The differences in the reliability index values, in this case, are about 42%. This may be inferred to the significant importance factor of the modulus of elasticity for clay e layer, which is about 41%.

The figure also shows that the increasing uncertainty level represented in COV leads to a considerable decrease in the reliability index by about 40%. It can also be concluded that within this reasonable range of COV (20-30%), the probability of failure increases by three times.

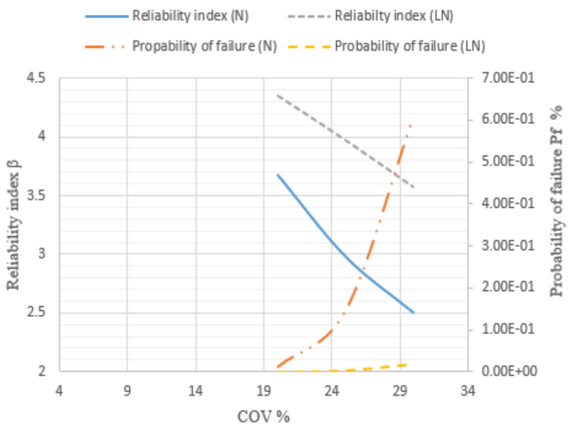


Figure 17 Reliability index and probability of failure for varying (E) COV for two types of distributions.

It is worth mentioning that carrying out the reliability analysis using the highest values of the COV for both of angle of friction and modulus of elasticity (15-30%) respectively resulted in a reliability index of 5.01, which is greater than the reliability index from section 6.2 by about 26%. While carrying out the reliability analysis, using the lower values of the COV for both of angle of friction and modulus of elasticity (5-20%) respectively resulted in a reliability index of 3.21, which is smaller than the reliability index from section 6.2 by about 19%.

7. CONCLUSIONS

The present work demonstrates a reliability analysis using FEM calculations for the port-said east port diaphragm quay wall. A developed technique was used for coupling the uncertainty source, PTK, and PLAXIS 2D V20 via a Python code interface. The effect of varying the statistical data for soil parameters such as the coefficient of variation and the distribution type was checked. Based on this study, the following conclusions could be drawn:

- The coefficient of variation for soil parameters may have a wide range according to the accuracy of the experimentation and the used correlations. The used value considerably affects the reliability results.
- The type of distribution leads to a different reliability result. So, determination of the distribution type may be crucial in defining the reliability level.
- Increasing uncertainty level represented in COV leads to a considerable decrease in the reliability index by about (20% - 40%).
- Increasing uncertainty level represented in COV leads to a considerable increase in the probability of failure by about (100% - 300%).

Credit Authorship Contribution Statement:

Mohamed Hamed: Generating the idea, collecting data, Methodology & Original draft preparation, Mohamed El-Gendy: Reviewing & Supervision, Ehab Tolba and Elsayed Galal: Validation, Editing, Reviewing & Supervision

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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