Reliability of mooring dolphin structures: an insight into partial safety factors

Fiabilité des structures d'accostage dauphin: un aperçu sur les facteurs partiels de sécurité

R. el-Bordany
Housing &Building National Research Center, Giza, Egypt

M. el-Meligy
Faculty of Eng., Mansoura University, Dakahlia, Egypt

A. Haldar
Dept. of Civil Eng. & Eng. Mech., University of Arizona, Tucson, USA

ABSTRACT

The steel-pile-soil-system as a mooring dolphin structure is an important element of marine structures. However, the reliability of this system is very difficult to predict due to inherent uncertainties in the marine environment. The objective of this paper is twofold; (i) to investigate the influences of several sources of uncertainties on different limit states of a steel-pile-soil mooring dolphin under axial and lateral loading conditions and (ii) to suggest partial safety factors required for the codified design. In doing so, the response surface method, RSM is used in reliability analysis. A grid of sampling response points is obtained from a realistic built up NLFEM. Then, this grid is used to formulate a response function equivalent to the implicit limit state function With the help of realistic examples, the most important random variables and limit state are identified. For routine design, partial safety factors are proposed.

RÉSUMÉ

Le système «sol-pile-acier» appelé aussi «accostage dauphin» est utilisé comme une structure d'amarrage. Il est un élément important parmi structures maritimes. Toutefois, la fiabilité de ce système est très difficile à prévoir en raison d'incertitudes dans l'environnement marin. L'objectif de ce papier est double: (i) d'enquêter sur les influences de plusieurs sources d'incertitudes sur les différents états limites d'une pile d'acier, du sol et de l'amarrage dans des conditions de chargement axiale et latérale (ii) de suggérer des facteurs de sécurité partielle nécessaires pour une conception normée. Pour ce faire, la méthode de réponse en surface est utilisée comme moyen d'analyse de fiabilité. Comme réponse une grille de points d'échantillonnage est obtenue à partir d'un Méthode non linéaire par éléments finis construit de façon réaliste. Ensuite, cette grille est utilisée pour formuler une fonction de réponse qui équivaut à l'état limite implicite. Avec l'aide d'exemples réalistes, le plus important des variables aléatoires ainsi que l'État limite sont identifiés. Pour la conception de routine, des facteurs de sécurité partielle sont proposés.

Keywords : response surface method, steel-pile-soil-system, soil-structure interaction, reliability analysis. partial safety factors.

1 INTRODUCTION

The Steel piles embedded in soil are an integral part of offshore foundation structures to carry mooring loads. The behavior of such complicated structural system is highly affected by the inherent uncertainties of the design variables related to the loading conditions, soil and pile material properties as well as the pile-soil interaction behavior. Considering the presence of large amount of uncertainties, deterministic design of steel-pile-soil system may not be desirable. However, they can be design to satisfy acceptable reliability-based design criteria producing economic design and reducing the likelihood of unexpected failures of existing structures preventing unpredictable and sometimes catastrophic consequences.

In any reliability-based design, appropriate limit states must be defined. However, considering the complexity of the problem, they cannot be defined explicitly. For implicit limit states, Haldar & Mahadevan (2000), suggested to approximately generate them using the response surface method, RSM. However, the basic RSM becomes very inefficient if it cannot be constructed in the failure region. The first order reliability method (FORM) is generally used to iteratively locate the failure point. To assure its efficiency, it is proposed in this paper that RSM needs to be integrated with FORM Huh & Haldar (2002), Lee & Haldar (2003). The RSM is started by generation some response points by calling a prepared FE model. Then, the commercial code; STATISTICA (2008), is used to formulate the implicit limit states using the obtained sample points. Finally, COMREL (1997), is used in the reliability analysis.

Uncertainties associated with geometric details, material properties and loading conditions are taken into account. In addition, the limit states of the lateral drift, shear, and flexural are considered. For numerical evaluation, the reliability of a real-life steel-pipe pile under axial and lateral mooring loads is estimated. The most critical limit state and the most sensitive design variables are identified. For routine design, partial safety factors are also proposed satisfying the reliability requirements.

2 RESPONSE SURFACE METHODOLOGY

In reliability analysis of such complex structures, the implicit limit state can be evaluated using the response surface method, Bucher & Bourgand (1990). In this method, the implicit limit state is function in the basic random variables. Their relations can only be determined by the FE algorithm. The superiority of FEM to model the complex mechanical behavior of steel-pipe-pile-soil system including different sources of nonlinearity such as; geometry, material and contact, is functioned to construct a grid of sample points on the actual (but implicit) limit state function. This grid is used to formulate an explicit equivalent surface. Then the equivalent and explicit limit state function is used to compute the reliability index. The actual limit state is replaced by a quadratic polynomial Equation 1 which may be enhanced by addition of the mixed terms Equation 2.

$$Q(X) = b_0 + \sum_{i=1}^{n} b_i X + \sum_{i=1}^{n} b_{ii} X^2 \tag{1}$$

$$Q(X) = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} b_{ii} X_i^2 + \sum_{i \neq j}\sum b_{ij} X_i X_j \tag{2}$$

$$X_i = \overline{X}_i \pm h\sigma_i \overline{X}_i \tag{3}$$

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where X_i $(i = 1, 2,\ldots, k)$ is the ith random variable; k = the number of basic variables; b_0, b_i, b_{ii}, b_{ij} = are unknown coefficients to be determined; $\overline{X}_i$, σ_i = the mean values and standard deviation of the basic random variables, respectively.

The polynomial can be completely defined by applying the regression analysis using the response of the system at the grid points. The selection of these sampling points is called experimental plan or design. However, these grid points should be selected as close as possible to the failure point/center point, a requirement that is not available at the beginning. Bucher & Bourgand (1990) suggested (i) using the mean value of the random variables as an initial center point. Also, the other points can be selected using some multiple of the standard deviation of the random variables according to Equation 3. (ii) Then a linear interpolation scheme is functioned and continued, until a preselected convergence criterion is satisfied i.e. the failure point is determined.

Selecting the design along with the polynomial determine the repeated deterministic FE analysis as well as governs the accuracy, efficiency and the practicality of the RSM. Two promising schemes were proposed and recommended by Huh & Haldar (2001) and a new one is suggested in the present paper. These schemes can be summarized as follow:

Scheme-1: SD using 2nd order polynomial in intermediate iterations and SD using 2nd order polynomial with cross terms in the final iteration.

Scheme 2: SD using 2nd order polynomial in intermediate iterations and CCD using 2nd order polynomial with cross terms in the final iteration.

M- Scheme: SD using 2nd order polynomial with cross terms of the most important variables through the whole iterations.

The three schemes need $p_1 = 2k+1$, $p_2 = (k+1)(k+2)/2$ and $p_3 = 2k+m$ FE calls to define the coefficients of the polynomials, respectively where m the number of the most important variables, MIV.

3 NLFE MODEL

To model the steel-pile-soil system using the COSMOS/M, (2000), the soil domain should be determined first, the soil domain is determined by plotting a relation between the changes of the system response to the increase of soil domain. Then, the soil domain is chosen based on the criterion that increasing the soil domain more than a certain value causes negligible change in the system response. In doing that, the far boundaries of soil is represent first using rollers then spring boundary elements are used to realistically represent the far soil field. Obviously, it is acceptable to represent these spring elements linearly for the far field soil domain. The soil can only be represented physically using solid element. The druker Prager constitutive law represents the soil nonlinearity in this solid element. On the other hand, the steel–pipe-pile was tried to be presented by shell element in order to be as realistic as possible, however this representation dramatically increase both the number of contact elements and the time of FE run. Therefore, the contact is physically represented by node to curve; the pile is represented by 3-D beam elements, which indicate the proposed finite element types along with their suggested constitutive models. The Hook`s law is acceptable from structural point of view to represent the behavior of pile material under the considered working load. Also, the strength of the steel pile is so large in comparison to that of soil.

For the contact problem, there are various contacts constitutive laws to represent the pile –soil contact problem, such as Lagrange multiplier and penalty function. On one hand, the penalty function method introduces large numerical values into the stiffness matrix of the system to simulate the rigidity between the two contacted nodes. A major difficulty arises in the selection of the proper penalty values. On the other hand, the Lagrange multiplier method incorporates new variables (Lagrange multipliers), causing increase in the stiffness matrix bandwidth. (COSMOS/M 2000), uses a hybrid technique which does not require assigning penalty values and at the time keeps the matrices size and width unchanged.

3.1 *Limit states*

In such problems, the reliability of steel-pipe-pile can be expressed by top drift serviceability limit state; and two ultimate limit states; flexure and shear. These three limit states can be expressed as:

$$G(x) = X_{all} - Q(x) \tag{4}$$

$$G(f_y) = f_y / \gamma - Q(f_y) \tag{5}$$

$$G(T_{xy}) = q / \gamma - Q(T_{xy}) \tag{6}$$

where; $G(x)$, $G(f_y)$, $G(T_{xy})$ = the drift, flexural and shear limit state functions, respectively; $Q(x)$, $Q(f_y)$, $Q(T_{xy})$ = are the drift, flexural and shear response surface functions, respectively; X_{all}, f_y, q = are the allowable drift, flexural and shear yield strength respectively; γ = reduction factor for steel strength.

4 STATISTICAL MODEL

The flexural, shear capacity and deformation behavior of steel-pipe-pile soil system, depends on the given loads, the material behavior the geometrical data as well as their statistical properties. Therefore these properties are reviewed in the literature. Then, appropriate values are chosen to build up the statistical model.

The mooring vertical and lateral forces, which depend on the Design Vessel, are calculated by the designer straight forward. This case of loading was found to be the most critical case of loading.

Uncertainty associated with steel pile variables, such as, the modulus of elasticity of steel, the cross sectional area expressed in terms of the internal and external radii of the pile and the unit weight of steel are considered to be random variables.

In general, the uncertainties associated with soil properties are expected to dominate the problem under consideration. In the present work, the probabilistically representation of the soil layers; modulus of elasticity, E the cohesion, C and friction angle, ϕ are assumed to have log-normal distributions with coefficients of variation COVs, 0.21, 0.37and 0.20, respectively., while, the unit weight, γ_s is assumed to have log normal distribution with COV equals 0.1, Probabilistic Model Code(2006), Réthátí (1995).

5 PARTIAL SAFETY FACTORS

Generally, there are two types of partial safety factors, PSF, one for load variable and the other for the strength variable. The load PSF is the factor by which the load variable is multiplied to achieve a target reliability index. While, the strength, PSF, is the factor by which the strength variable is divided to achieve a target reliability index (COMREL & SYSREL 1996); i. e.,

$$\gamma_{li} = \frac{x_i^*}{x_{c,i}} , \quad \gamma_{si} = \frac{x_{c,i}}{x_i^*} \tag{7}$$

where: γ_{li}, γ_{si} = the loading and the strength partial safety factors, respectively; $x_{c,i}$ = characteristic value of the random variable x_i;= design value of the random variable.

6 APPLICATION EXAMPLES

6.1 *Example 1: Theoretical Example*

In order to illustrate the suggested scheme, a simplified theoretical example that has closed form solution is assumed for the sake of comparison. It consists of a steel- pipe- pile of uniform hollow cross section, derived in a homogenous elastic soil. The stochastic model of this simplified example is given in Table 1. first the reliability index β for the drift is computed using the closed form solution which found in many foundation text books, Desai &. Christian (1997).

For the sake of comparison, the system is modeled in FE as a beam model on elastic foundation. Then, the three pre mentioned response surface schemes are used to compute the reliability of this soil-pile system. At the beginning of response surface method, it is a good practice –as the number of random variables is relatively large- to use the 2n+1 grid points with a linear polynomial in a preliminary reliability analysis. This preliminary step enables the analyst to eliminate the non-important variables and simplify the problem. As a result the number of random variables is reduced from 9 to 5. So, the β-indices are 3.491 and 3.343 for scheme 1 & 2 using 2n+1 = 19 and 2n+1+(m)(m-1)/2 = 29 FE calls, respectively.

The M-scheme suggestion is not to make all the m(m-1)/2 FE calls of the scheme 2, but make the runs corresponding to the most important variables, MIV. In other words, it suggests taking the interaction of the important variables only into account. In this example, the MIV is the horizontal load, H, see Figure 1, which shows the relative importance of the different variables. According to the suggestion, the FE calls corresponding to the interaction of the H with the other 4 MIVs, i.e. 4 runs. This yields β-index=3.383 (point1 in Figure 2). Therefore, the three schemes yields β-indices 3.491, 3.343 and 3.383 using 19, 29 and 23 FE calls, respectively. The reliability indices of the three schemes are 92.02%, 96.6% and 95.4% of β-closed form solution, respectively. To increase, the accuracy, the interaction of the second MIV with other variables is taken into account. In other words, the point 2 in Figure 2, shows the improvement in β-index, if the runs of the second MIV, soil modulus of elasticity, E1,(3 runs) are added. Obviously, the improvement in β-index is dependent on the importance of the variables. By the same way point 3, shows the effect of adding the runs of third MIV, pile radius, r, (2runs) and so on.

Table 1. Stochastic model

No	Variable, X_i		Dist..	Mean	COV	Ref.
1	Lateral load	H	EV-I	150 t	0.25	*
2	Vertical load	V	N	10 t	0.25	*
3	Radius	r	N	0.95 m	0.03	*
4	Thickness	t	N	2.8 cm	0.03	*
5	Height	L	N	41.2 m	0.01	*
6	Steel E-modulus	E_s	LN	2.01E7 t/m^2	0.04	14
7	Steel density	γ_s	LN	7.881 t/m^3	0.10	14
8	Soil E-modulus	E_l	LN	150 t/m^2	0.21	12,15
9	Soil density	γ_l	LN	1.6 t/m^3	0.10	12,15

* Data not available. Assumed parameters are based on judgment.

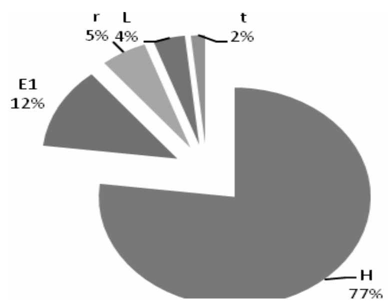

Figure 1. Relative importance of MIV

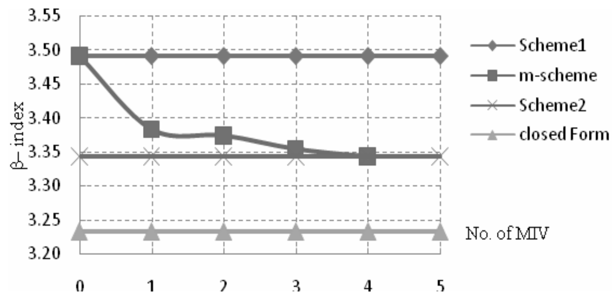

Figure 2. β-index for the closed form, and the three schemes

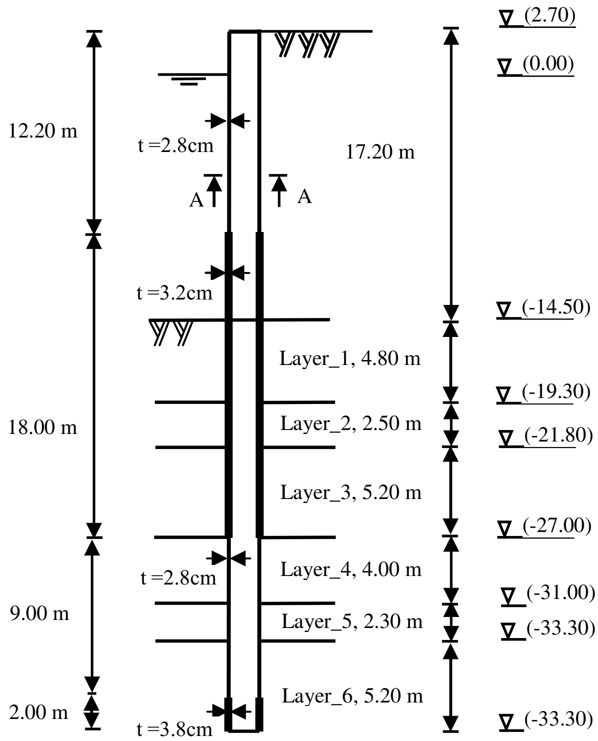

Figure 3. Layout of the pile-soil system

Table 2. Properties of the soil layers

	E- Modulus t/m^2	C t/m^2	ϕ (degree)
Layer 1: Soft clay	120	3.25	---
Layer 2: Medium clay	500	3.55	---
Layer 3: Stiff clay	700	5.15	---
Layer 4: Very dense sand	16500	---	---
Layer 5: Very stiff clay	2000	12	35
Layer 6: Very dense sand	26000	---	---

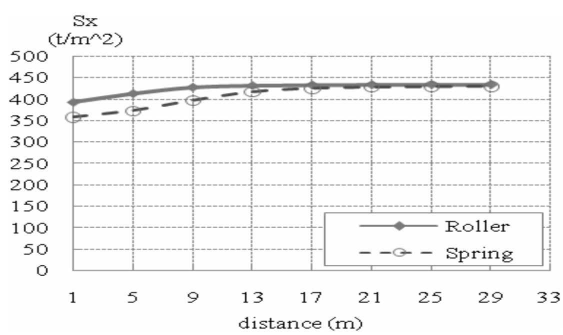

Figure 4. Soil domain

6.2 *Example 2: Real Life Example*

A Mooring dolphin in Damietta harbor, Egypt is chosen to demonstrate the proposed method. The soil parameters reported by a consulting engineer are used in the study. All the related data of the example are real; see Figure 3 and Table 2 for geometrical details and the soil properties, respectively.

As allowed by symmetry, half the problem is considered. Figure 4, shows that the effect of the spring elements on the soil maximum horizontal stress, Sx, decreases with increase the horizontal dimension of soil (17 m is chosen). The model is shown in Figure 5. The response (drift, U and moment M), by the used Program COSMOS/M (2000) and the program used by of the designer, SARGON, are shown in Figure 6, where the two cases are termed as L and SARAGON, respectively. Then, two cases are analyzed; the soil nonlinearity without contact element and the soil nonlinearity with contact elements, termed as NL, and CNL, respectively. It is obvious that the contact elements have no effect that is because the soil elements do not resist tension, and play the same role as the contact elements. So, the two cases can be considered the same. Finally, Table 3 shows the complete stochastic model. In RSM, the most time consuming task is the NLFE calls. It governs the time of the RSM. As an example, in this problem while the linear FE model run, takes 3 minutes, the NL run takes 4 and 5.5 hours for model without and with the contact elements, respectively. These shows the time required for each scheme.

Table 4 shows for the three limit states; drift, moment and shear in the two cases of analysis; the β-indices; the most important variables, MIVs and the computed partial safety factors. It is evident that the lateral mooring loads dominates the response. Comparing these values with the available codes can help to update the codes from reliability point of view.

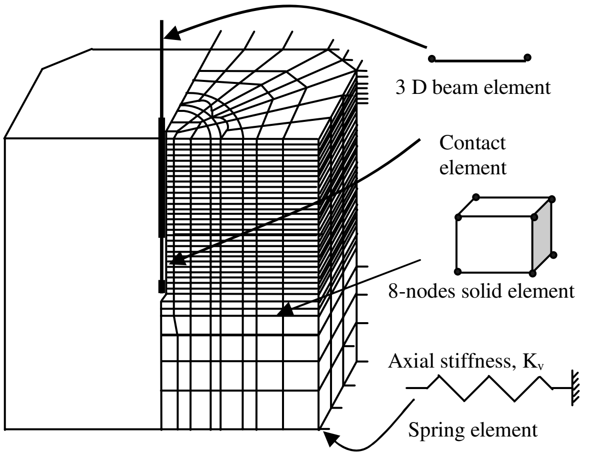

Figure 5. Multi-discretization Finite element model of Pile-Soil system

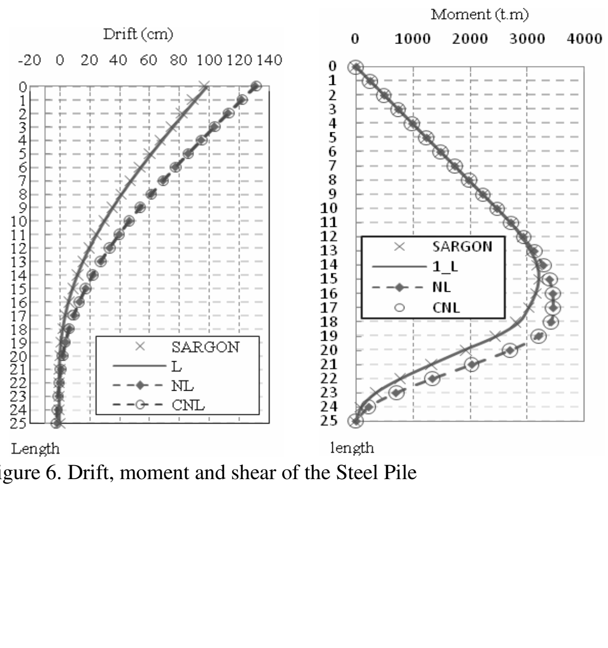

Figure 6. Drift, moment and shear of the Steel Pile

Table 3. Stochastic model

No	Random variables		Dist.	Mean	COV	Remarks
1	Lateral load	H	EV-I	150 t	0.25	*
2	Vertical load	V	N	10 t	0.25	*
3	Radius	r	N	0.95 m	0.03	*
4	Thickness	t	N	2.8 cm	0.03	*
5	Height	L	N	41.2 m	0.01	*
6	Steel E-modulus	E_s	LN	2.01E7 t/m^2	0.03	
7	Steel density	γ_s	LN	7.881 t/m^3	0.01	
8	Soil E-modulus	E_1	LN	120 t/m^2	0.21	
9	Soil density	γ_1	LN	1.6 t/m^3	0.10	
10	Cohesion	C_1	LN	3.25 t/m^2	0.37	
11	`Soil E-modulus	E_2	LN	500 t/m^2	0.21	
12	Cohesion	C_2	LN	3.55 t/m^2	0.37	
13	Soil density	γ_2	LN	1.6 t/m^3	0.10	
14	Soil E-modulus	E_3	LN	700 t/m^2	0.21	
15	Cohesion	C_3	LN	5.15 t/m^2	0.37	
16	Soil density	γ_3	LN	1.85 t/m^3	0.10	
17	Soil E-modulus	E_4	LN	16500 t/m^2	0.21	
18	Friction angle	ϕ_4	LN	35°	0.20	
19	Soil density	γ_4	LN	1.85 t/m^3	0.10	
20	Soil E-modulus	E_5	LN	2000 t/m^2	0.21	
21	Cohesion	C_5	LN	12 t/m^2	0.37	
22	Soil density	γ_5	LN	1.8 t/m^3	0.10	
23	Soil E-modulus	E_6	LN	26000 t/m^2	0.21	
24	Friction angle	ϕ_6	LN	35°	0.20	
25	Soil density	γ_6	LN	1.9 t/m^3	0.10	

* Data not available. Assumed parameters are based on judgment.

Table 4. Stochastic model

	Analysis	U	M	Q
β	L	3.485	2.382	7.487
	NL	2.241	2.766	6.301
MIV	L	H, r, L, 85%, 8%, 7%	H, r, t 87%, 9%, 4%	H, r, t, 78%, 11%, 11%
	NL	H, r, L, 86%, 9%, 5%	H, r, t 84%, 8%, 8%	H, r, t, 82%, 9%, 9%
PSF	L	1.86	1.69	1.69
	NL	1.56	1.56	1.56

7 CONCLUSION

A new response surface scheme is suggested. Its accuracy and efficiency are proven to be comparable with the other schemes through a theoretical example. Further more, the reliability of a mooring dolphin, steel-pipe –pile type, from the real life is investigated. The critical variables are determined. More over a suggestion for the partial safety factors is introduced. In the NLFE model, it is found that the introduction of the contact elements has immaterial effect. As the soil itself resist no tension and behave similar to the contact elements.

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