Sensitivity Analysis of Selected Random Variables of Existing Offshore Jacket Structures in Persian Gulf

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Abstract

Structural integrity evaluation of an existing offshore platform typically is based on a combination of non-linear structural analysis together with risk and reliability analysis. Quantitative assessment of the probability of failure of a jacket platform under extreme metocean loads is a multi-disciplinary task, poses significant challenges and involves a large number of uncertainties regarding the metocaen hazards, structural system and modelling, loads, material behaviour and geotechnical information. The probability of failure is commonly estimated using a reliability analysis to account for uncertainties in derivation of both the loading and the strength.

Different sources of uncertainties contribute to the platform ultimate strength. Sensitivity analysis should be carried out to provide quantitative information necessary for classifying random variables according to their importance. These measures are essential for reliability-based service life prediction of deteriorating materials and structures. Accordingly, in this paper, Tornado approach has been used to identify those variables that affect the failure most so that more research can focus on those variables. To this end, six existing offshore platforms located in Persian Gulf are investigated. The results have been presented in the form of a Tornado diagram which will graphically show the sensitivity of the target function to each random variable.

Keywords: Structural integrity, Sensitivity analysis, Random variables, Existing offshore structures.

1. Introduction

Structural integrity assessment is an ongoing procedure to ensure the reliability of the offshore structures and the safety of their operation. A significant number of researches have been carried out on the structural assessment of existing offshore platforms subjected to extreme loading [Ref. 1][Ref. 2][Ref. 3]. Since offshore structures require more critical and complex designs, the need for accurate approaches to evaluate uncertainty in loads, geometry, and material properties has increased significantly [Ref. 4]. The effect of variables on the reliability of an existing offshore platform can be analysed by doing a comprehensive sensitivity analysis. In view of the large number of variables that affect the aging/collapse process and limit states, it is of interest to identify those variables that affect the failure most. Sensitivity analysis is widely accepted as a necessary part of reliability analysis of structures and infrastructures [Ref. 5][Ref. 6][Ref. 7][Ref. 8]. Sensitivity analysis is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation [Ref. 9]. Among the reasons for using sensitivity analysis are:

• To identify the factors which have the most influence on reliability of the structure.
• To identify factors that may need more research to improve confidence in the analysis.
• To identify factors which are insignificant to the reliability analysis and can be eliminated from further analysis.
• To identify which, if any, factors or groups of factors interact with each other.

To the best authors' best knowledge, sensitivity analysis has not yet been investigated for existing offshore structures. Accordingly, in this paper, a comprehensive study on the sensitivity analysis of steel jacket structures located in Persian Gulf has been carried out.

2. Sensitivity Analysis

Sensitivity analysis provides the degree of variation of limit state functions or measures at a specific point characterized by a realisation of all random variables. Similarly to the conventional sensitivity measure in the reliability approaches, the sensitivity measure, S, can be defined as follows [Ref. 10]:

$$S_{G(X)}(X_i) = \frac{\partial G(X)}{\partial X_i} = \lim_{\varepsilon \to 0} \frac{G(X+\varepsilon) - (G(X)}{\varepsilon} \tag{1}$$

Where G is a performance function of X: X and ε are vectors; and ε is a small perturbation. An element X_i of X can be any type of variable or parameter. For instance, it can be a mean or a standard deviation of a variable, or a deterministic parameter. For a complex system, the sensitivity measure can be computed by using the numerical differentiation method rather than by an analytical approach [Ref. 10]. Different sensitivity approaches have been introduced. In the current research, Tornado methedology will be discussed and will be used.

3. Tornado Approach

Tornado approach can be used to show the sensitivity of the response to each random variable, graphically [Ref. 11]. It produces something called a tornado diagram that depicts the approximate effect of each uncertain on the quantity of interest. The method comes from the field of decision analysis. Its first proposed use in earthquake engineering may be by the present author [Ref. 12][Ref. 13], and it has been used in performance-based earthquake engineering and seismology a few times since then.

Here first is a description of the procedure [Ref. 13]. Briefly, one selects a low, typical, and high value of each input parameter. One then estimates the output parameter using typical values of all the inputs except one, which is set at its low value. Repeat the process with the same input set at its high value. The difference between the last two outputs is referred to as the swing associated with the one input that was varied. That input is then set back to its typical value and the process is repeated for the next input, again setting all the other inputs to their typical value. A horizontal bar chart is then created by depicting the swing associated with each input variable as a bar whose ends are at the low and high values of the output produced by changing just that input. The *x*-axis is the value of the output. The bars are arranged with the input that has the highest swing on the top, then the input with the second-highest swing, etc.

More precisely, suppose a function for a quantity *y* wanted to study [Ref. 13]:

$$y = f(x_1, x_2, \dots, x_i, \dots, x_n) \tag{2}$$

For each random variable x_i, three values including $\mu - \sqrt{3}\sigma$, μ, $\mu + \sqrt{3}\sigma$ are taken into account, where μ and σ denote the mean/median and standard deviation of each random variable, respectively.

$$y_{baseline} = f(x_{1typ}, x_{2typ}, \dots, x_{ityp} .. x_{ntyp}) \tag{3}$$

This is the baseline value, now conducting the sensitivity of y to the uncertainty in each x:

$y_{1low} = f(x_{1low}, x_{2typ}, \dots, x_{ityp} .. x_{ntyp})$ i.e., all typical values except using x_{1low} (4)

$y_{1high} = f(x_{1high}, x_{2typ}, \dots, x_{ityp} .. x_{ntyp})$ i.e., all typical values except using x_{1high}

$y_{2low} = f(x_{1typ}, x_{2low}, \dots, x_{ityp} .. x_{ntyp})$ i.e., all typical values except using x_{2low}

$y_{2high} = f(x_{1typ}, x_{2high}, \dots, x_{ityp} .. x_{ntyp})$ i.e., all typical values except using x_{2high}

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$y_{ilow} = f(x_{1typ}, x_{2typ}, \dots, x_{ilow} .. x_{ntyp})$ i.e., all typical values except using x_{ilow}

$y_{ihigh} = f(x_{1typ}, x_{2typ}, \dots, x_{ihigh} .. x_{ntyp})$ i.e., all typical values except using x_{ihigh}

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$y_{nlow} = f(x_{1typ}, x_{2typ}, \dots, x_{ityp} .. x_{nlow})$ i.e., all typical values except using x_{nlow}

$y_{nhigh} = f(x_{1typ}, x_{2typ}, \dots, x_{ityp} .. x_{nhigh})$ i.e., all typical values except using x_{nhigh}

Then with a quantity called swing the sensitivity of y to uncertainty in each x can be evaluated:

$$Swing_1 = \left| y_{1low} - y_{1high} \right| \tag{5}$$

$$Swing_2 = \left| y_{2low} - y_{2high} \right|$$

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. $Swing_i = \left| y_{ilow} - y_{ihigh} \right|$

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$$Swing_n = \left| y_{nlow} - y_{nhigh} \right|$$

By sorting x parameters in decreasing order of swing, a horizontal bar chart namely Tornado diagram is generated. The uppermost (top) horizontal bar in the diagram measures y_i with where *i* is the index for the input parameter with the largest swing.

The next horizontal bar measures y_j where j is the index for the x-parameter with the 2nd-largest swing. The result looks like a tornado in profile. Drawing a vertical line at $y_{baseline}$, one can explore the 2 or 3 or 4 x-parameters that matter most, and ignore the rest or treat them more casually, that is, with less effort to quantify or propagate their uncertainty.

4. Modelling and Methodology

4.1 Case studies

This paper presents a number of case studies for the sensitivity analysis of existing aging drilling platforms located in the Persian Gulf. The platforms, typically, are now around 40 years old and the objective of the study is to to identify the factors which have the most influence on reliability of the structure and its fit for purpose for a life extension.
Figure 1 and Table 1 give the overall views and specifications of the platforms, respectively.

AA, Production Platform (6-Legged)

2S-19, Wellhead Platform (3-Legged)

R1-NSP, Service Platform (4-Legged)

Nasr-N2, Drilling Platform (6-Legged)

Nasr-LQ, Living Quarter (4-Legged)

Nasr Production Platform (6-Legged)

Figure 1: Overall views of the studied platforms

4.2 Numerical Modeling

Three-dimensional structural model of the platforms have been generated using SACS software [Ref. 14]. The structural model is based on the best estimates of the existing conditions of the platforms. The models incorporate all primary and secondary steel structural members in the topside and in the jacket part such as legs, vertical and horizontal bracings, piles, the deck main girders and truss members. Those members that do not contribute significantly to the structural stiffness and load bearing such as boat landing, stiffeners, handrails, deck gratings, stairs, ladders, etc. have been modelled as dummy elements or their environmental and gravitational loads have been taken into consideration .
Some other considerations and assumptions used in the modelling are as follow:

• The effect of including local joint flexibility in the assessment of an existing offshore structure can significantly reduce uncertainties on calculated fatigue lives at tubular joints especially for joints in horizontal frames [Ref. 15]. in the current study, the joint flexibility has then been considered.

• The model also incorporates structural anomalies discovered in the underwater survey. Anomaly modelling for the cracked and the perforated members are based on general guidelines and the methodology provided by ABS for the ultimate strength of the perforated members [Ref. 16].

• For the members located in the splash zone of the platforms, this corrosion allowance shall be added to the corrosions measured and reported by underwater survey reported. No corrosion thickness allowance will be considered for the structural members located below the splash zone.

• Gerwick [Ref. 17] reported that: "typical rates of corrosion of uncoated steel in seawater are 0.15 mm/year in the splash zone; 0.07 mm/year in the submerged zone. Other studies for uncoated steel in seawater give rates of 0.127 mm/year." On that basis, a corrosion thickness allowance has been considered for the structures.

• The effective buckling length of the members used in the calculation of axial allowable compressive stresses is in accordance with the recommendation of API RP 2A [Ref. 18]. The effective buckling length is calculated as the K-factor multiplied by the un-braced length of the member relative to in-plane or out-of-plane buckling. These factors are input relative to the corresponding local Y and Z axes of each member.

• Based on API RP 2A-17.7.2b [Ref. 18], for the structural assessment purposes, lower values for effective length (k) factors may be used when justified. This is because studies and tests have indicated that effective length (k) factors are substantially lower for elements of a frame than those specified in API RP 2A-3.3.1d. It is noted Eurocode 3 [Ref. 19] recommends an effective buckling length equal to 0.75L or less (where L is the member length) for hollow section brace members in welded lattice frames. For the Ultimate Strength assessment, the effective length (k) factors for K bracings, diagonals and X bracings were taken as 0.7 instead of the larger "k" values given in the API RP 2A [Ref. 18].

• The structures have been modeled considering structural steel material properties as specified in the Design Calculation Notes. As per API RP 2A- C17.7.3 [Ref. 18], for the Ultimate Strength Level analysis of the platform, instead of nominal yield strength, the mean yield strength of the steel material can be used. As an example, for A36 steel material, with the nominal, yield strength of 36 ksi (23.5 kN/cm2), mean yield strength of 42 ksi (27.5 kN/cm2) has been considered in the Ultimate Strength Level analysis. This is around 17% increase in material yield strength to account primarily for the increase from nominal to mean strength.

Table 1: Specification of the studied platforms

District	Field	Platform Name	Platform Activity	No. of Legs	Bracing Type	Soil Type	Installation Year	No. of Riser/ Conductors	Water Depth (m)
Sirri	Dena	Nasr-PP	Production	6	V-Shape	Silty Clay	1976	16	60.0
		Nasr-LQ	Living Quarter	4	Diagonal	Silty Clay	1990	----	60.0
		N2	Drilling	6	Diagonal		1976	10	59.0
Kharg	Aboozar	AA	Production	6	Diagonal	Sand-Clay	1976	6	37.0
Lavan	Salman	2S19	Wellhead	3	X-Shape	Sand	1973	3	35.0
	Resalat	R1-NSP	Service Platform	4	V-Shape	Sand-Clay	1970	5	67.0

4.3 Analysis Methodology

A number of Push-over analyses have been carried out to assess the platforms Ultimate Strength against metocean loadings. Metocean loads acting along the weakest direction (among the main eight directions in LAT and HAT modes). Primary load combinations are formed by combining basic load cases within the SACS Sea-state module prior to the analysis. Each load combination is then incrementally applied to the structures. Adjustments in the load increments are based on engineering judgments and the response of the structures.

The static Push-over analysis provides an insight on the load bearing performance of the platform, indicates the weak links, failure modes, the ultimate strength as well as the post-yield behavior of the structure. When a Push-over analysis is complete, the ultimate lateral load bearing capacity of the structure is expressed in terms of “Reserve Strength Ratio” (RSR) which is defined as:

$$RSR = \frac{Ultimate\,Lateral\,Load\,That\,Causes\ failure}{100\,Year\,Environmental\,Lateral\,Loading} \tag{6}$$

An Ultimate Strength analysis is generally believed to provide a balanced estimate of the platform load bearing capacity. The Ultimate Strength analysis may be carried out either as quasi-static analyses (push-over) or as dynamic time-domain analyses. For the Ultimate Strength Level assessments, metocean criteria are specified in terms of factors relative to resultant load from 100-year environmental conditions. The Reserve Strength Ratio (RSR) is used to specify the ultimate strength of the platform. RSR is the ratio of a platform’s ultimate lateral load carrying capacity to its 100-

year lateral environmental loading, as basis. The latter is computed using criteria, as described in API RP 2A-2.3, for new design [Ref. 18].

The "COLLAPSE" module of SACS [Ref. 14] is employed to carry out the non-linear quasi-static (Push-over) analyses. For the collapse (Push-over) analyses, which are load-path dependant, it is not possible to directly solve for structural actions at any instant, so an incremental analysis procedure is used. Hence, the loading was applied in a series of increments until global failure of the platform occurred. It is worth noting that Push-over results were presented based on Reserve Strength Ratio (RSR).

Different sources of uncertainties such as in the structural modelling, in the stress analysis, in the component capacity formulations, in the damage evaluation and its modelling, in the overall structural resistance, in the as-is condition data, in the knowledge about the platform inspection, maintenance and repair records, in the nonlinear software predictions accuracy, in the pile/soil interaction, in the foundation behaviour and capacity, in the material yield strength and module of elasticity, in the members actual dimensions and thickness, in the platform weight and its gravitational loads, etc contribute to the overall RSR uncertainty. Variability in some of these parameters is listed in Table 2.

Table 2: Statistical characteristics of some random variables which might have impacts on the platform probability of failure

Random Variable	Symbol	Mean / Median	Cov.	Type	Reference
Parameters influencing variability of the wave force on the structure					
Drag Coefficient	C_d	0.65, 1.10	0.25	Lognormal	[Ref. 20][Ref. 21]
Inertia Coefficient	C_m	1.60, 1.27	0.10	Lognormal	[Ref. 20][Ref. 21]
Marine Growth	MG	75mm, 50mm	0.50	Lognormal	[Ref. 20][Ref. 21]
Parameters influencing uncertainties in the structural model					
Load and Masses	M, W	Computed	0.10	Normal	[Ref. 21]
Yield Stress of Legs	$f_{y,L}$	335 MPa, 345 MPa	0.07	Lognormal	[Ref. 21]
Yield Stress of Braces	$f_{y,B}$	335 MPa, 345 MPa	0.07	Lognormal	[Ref. 21]
Modulus of elasticity	E_s	2.0601 x 10^5 MPa	0.03	Lognormal	[Ref. 21]
Parameters influencing uncertainties in the pile-soil interaction					
Undrained shear strength	C_u	*	0.3	Normal	[Ref. 22][Ref. 23]
Unit weight	γ	*	0.1	Normal	[Ref. 22][Ref. 23]
Strain occurs at one-half the maximum stress	ε_{50}	*	0.4	Normal	[Ref. 22][Ref. 23]
Friction angle	f	*	0.02-0.05	Normal	[Ref. 23]

5. Results and Discussion

The "COLLAPSE" module of SACS [Ref. 14] is employed to carry out the non-linear quasi-static (Push-over) analyses. For the collapse (Push-over) analyses, which are load-path dependent, it is not possible to directly solve for structural actions at any instant, so an incremental analysis procedure is used. Hence, the loading was applied in a series of increments until global failure of the platform occurred. It is worth noting that Push-over results were presented based on Reserve Strength Ratio (RSR). Different sources of uncertainties contribute to the platform ultimate strength or its normalized ultimate strength (RSR). To determine the prominent parameters affecting the behaviour of jacket platform, random variables listed in Table 2 has been taken into account. For each random variable of X_i, two extreme values of $\mu_i \pm \sqrt{3}\sigma_i$ are taken. Values of μ_i and σ_i denote the mean/median and the standard deviation of the random variable X_i, respectively. Then, the platform will be analysed separately for each of the extreme values of the random variable X_i and the corresponding target function is calculated. This procedure is repeated for all random variables considered in the problem. Table 3 to Figure 6: Tornado diagram showing the sensitivity of ultimate capacity of AA platform obtained from a pushover analysis

Table 8 and Error! Reference source not found. to Figure 7 give the tornado results and diagrams for the RSR and the ultimate strength of the platforms.

Table 3: Sensitivity Results of R1-NSP

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	2.90	6360	PP, SZP, PPO	1.45	7017	PP, SZP, PPT
C_m	1.89	6690	PP, SZP, PPO	1.91	6688	PP, SZP, PPT
MG	2.10	6800	PP,SZP,PPT	1.75	6650	PP, SZP, PPO
Mass	2.05	7190	PP, SZP	1.55	5488	PP, SZP, PPO
F_y	1.65	5820	PP,SZP,PPT	1.95	6860	PP, SZP, PPT
E	1.90	6686	PP,SZP,PPT	1.95	6862	PP, SZP, PPO
Soil	1.30	5100	PP, PPO	2.10	7398	PP, SZP
Base Case	RSR: 1.90		Base Shear (kN): 6692		Failure Mode : PP, SZP, PPO	

*PP: pile plasticity; SZP: splash zone plasticity; PPO: pile pull out; PPT: pile punch thru

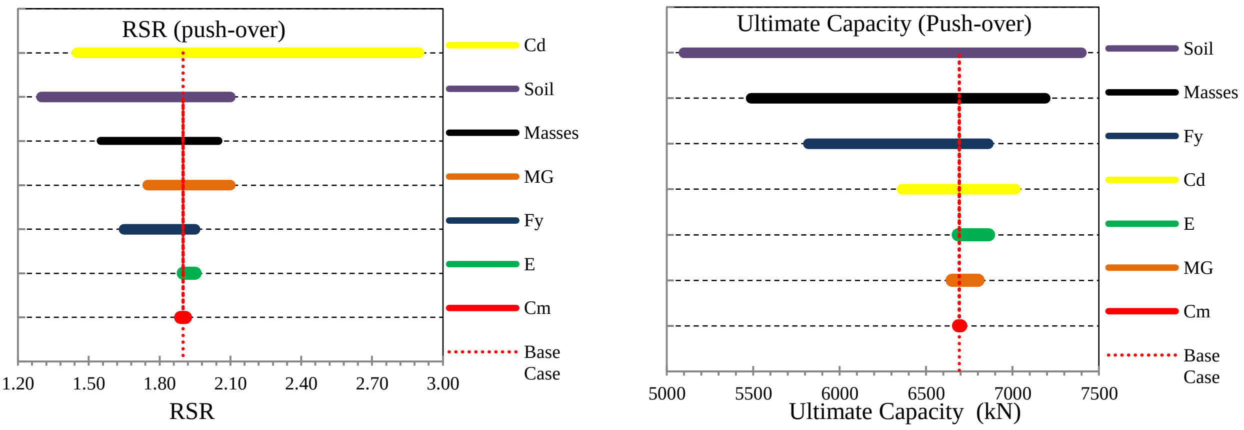

Figure 2: Tornado diagram showing the sensitivity of ultimate capacity of R1-NSP obtained from a pushover analysis

Table 4: Sensitivity Results of Nasr-PP

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	4.21	11051	PP, JP, PPT	2.01	11853	PP, JP, PPT
C_m	2.65	11250	PP, JP, PPT	2.67	11354	PP, JP, PPT
MG	3.30	11550	PP, JP, PPT	2.14	10736	PP, JP, PPT
Mass	2.98	12687	PP, JP, PPT	2.27	9605	PP, JP, PPT
F_y	2.72	11510	PP, JP, PPT	2.72	11540	PP, JP, PPT
E	2.59	11000	PP, JP, PPT	2.66	11275	PP, JP, PPT
Soil	1.65	7250	PP, JP, PPT	3.24	13778	PP, JP
Base Case	RSR: 2.66		Base Shear (kN): 11270		Failure Mode : PP, JP, PPT	

*PP: pile plasticity; JP: jacket plasticity; PPO: pile pull out; PPT: pile punch thru

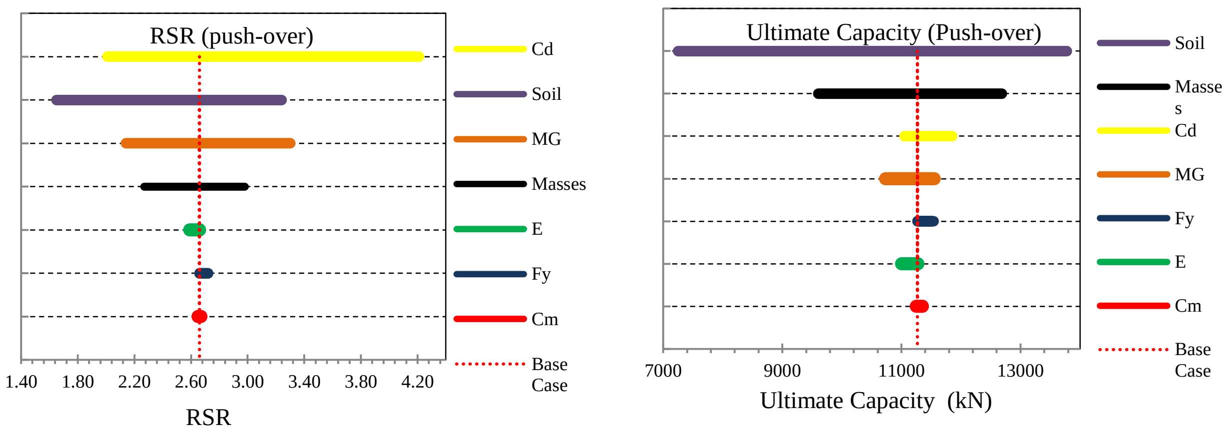

Figure 3: Tornado diagram showing the sensitivity of ultimate capacity of Nasr-PP obtained from a pushover analysis

Table 5: Sensitivity Results of Nasr-LQ Platform

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	4.56	6576	PP, PPT	2.28	6642	PP, PPT
C_m	3.12	6661	PP, PPT	3.08	6725	PP, PPT
MG	3.84	6878	PP, PPT	2.48	6329	PP, PPT
Mass	3.36	7297	PP, PPT	2.72	5880	PP, PPT
F_y	2.96	6414	PP, PPT	3.08	6666	PP, PPT
E	3.04	6576	PP, PPT	3.08	6666	PP, PPT
Soil	1.62	4200	PPT	3.72	7979	PP, JP
Base Case	RSR: 3.08		Base Shear (kN): 6664		Failure Mode : PP, PPT	

*PP: pile plasticity; SZP: splash zone plasticity; PPO: pile pull out; PPT: pile punch thru

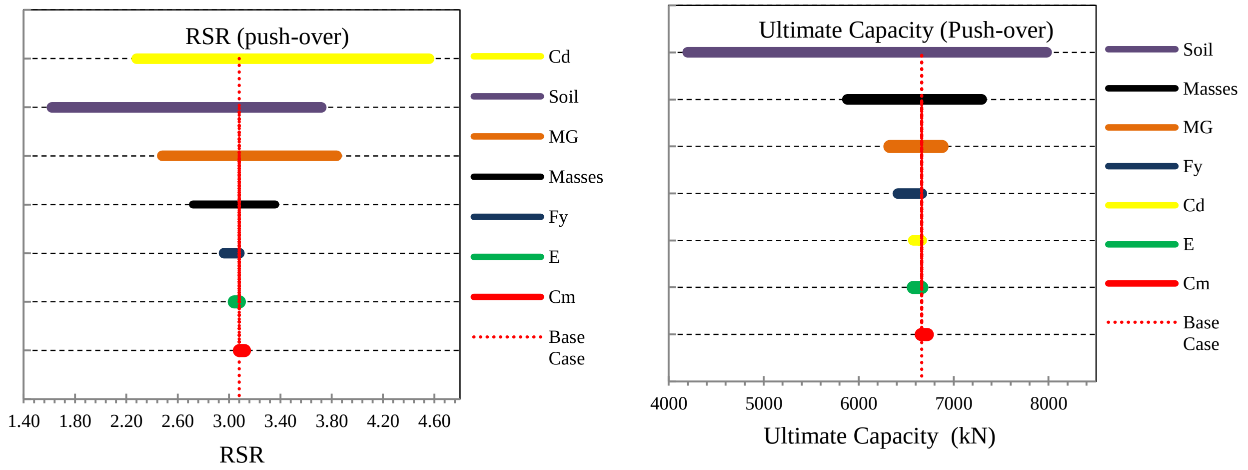

Figure 4: Tornado diagram showing the sensitivity of ultimate capacity of NASR-LQ obtained from a pushover analysis

Table 6: Sensitivity Results of N2 Platform

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	6.24	21155	PP	2.65	14838	PP
C_m	3.77	15127	PP	3.65	14844	PP
MG	4.65	16492	PP	3.17	15125	PP
Mass	3.81	14232	PP	3.77	14860	PP
F_y	3.49	15278	PP	4.05	16326	PP
E	3.77	15192	PP	3.77	15192	PP
Soil	2.89	11640	PPT, PPT	3.93	15695	PP
Base Case	RSR: 3.73		Base Shear (kN):14967		Failure Mode : PP	

*PP: pile plasticity; SZP: splash zone plasticity; PPO: pile pull out; PPT: pile punch thru

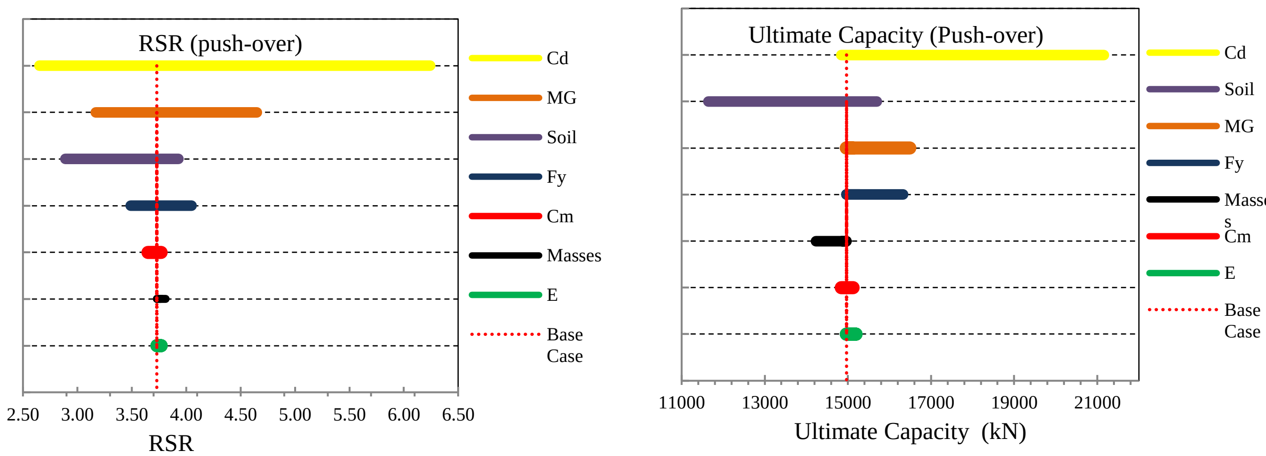

Figure 5: Tornado diagram showing the sensitivity of ultimate capacity of N2 platform obtained from a pushover analysis

Table 7: Sensitivity Results of AA Platform

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	3.00	10266	JP	1.60	12374	PP, PPT
C_m	2.26	12468	PP, JP	2.24	12340	JP
MG	2.36	11685	H, JP	1.66	10585	PP
Mass	2.04	11238	JP	1.90	10750	H, JP
F_y	1.82	10141	PP	2.44	13433	PP, JP
E	2.20	12113	H, PP, PPT	2.26	12267	H, PP, JP
Soil	1.30	8450	PP, JP	2.10	12569	PP, JP
Base Case	RSR: 2.24		Base Shear (kN): 12340		Failure Mode : PP, JP	

*PP: pile plasticity; JP: Jacketplasticity; PPO: pile pull out; PPT: pile punch thru; H: hinged

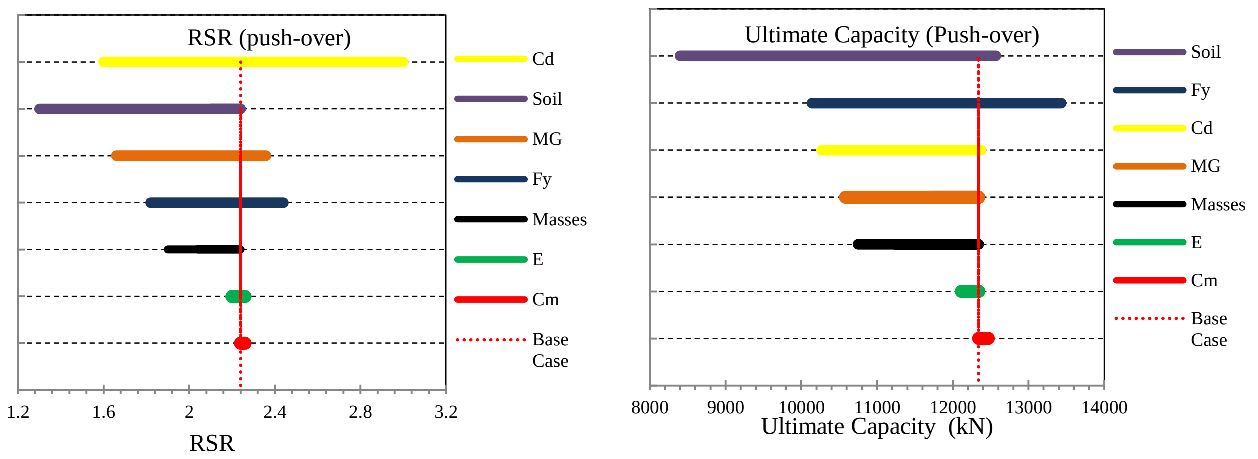

Figure 6: Tornado diagram showing the sensitivity of ultimate capacity of AA platform obtained from a pushover analysis

Table 8: Sensitivity Results of 2S-19 Platform

Parameter	Lower Results			Upper Results		
	RSR	Base Shear (kN)	Failure Mode*	RSR	Base Shear (kN)	Failure Mode*
C_d	2.78	1965		1.12	1950	
C_m	1.62	1968		1.60	1956	
MG	1.72	1960		1.52	1964	
Mass	1.62	1964		1.56	1916	
F_y	1.52	1873		1.64	1992	
E	1.62	1966		1.60	1954	
Soil	1.12	1354		2.06	2538	
Base Case	RSR: 1.62		Base Shear (kN): 1976		Failure Mode:	

*PP: pile plasticity; SZP: splash zone plasticity; PPO: pile pull out; PPT: pile punch thru

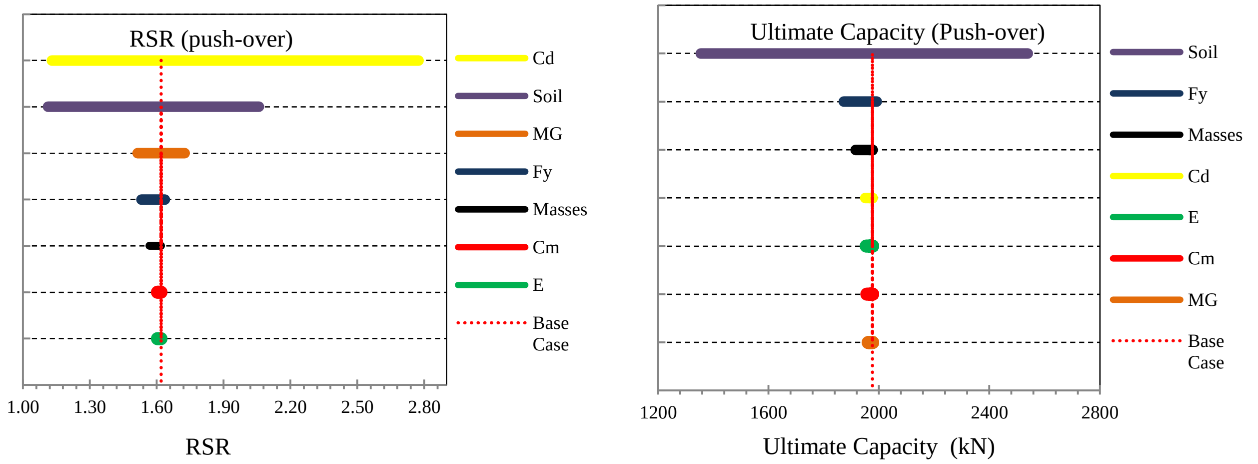

Figure 7: Tornado diagram showing the sensitivity of ultimate capacity of 2S-19 platform obtained from a pushover analysis

6. Summary and conclusions

Main conclusions of the conducted sensitivity analyses can be summarized as below:
- Among all random variables, Drag Coefficient (C_D) has been the most significant variable which affects the RSR. It should be noted that according to the RSR definition (See equation 6), it depends on two parameters; environmental loading and the capacity of the structures.
- Among all studied random variables, soil has most impact on the Ultimate Capacity of the structures. It may worth mentioning that as in can be seen from Tornado diagrams, C_D is not important for RSR. This is because it only affect the environment loading (See equation 6). Moreover, it has been concluded that soil is a too sensitive variable and any little change in this parameter can noticeably affect the ultimate strength of structures.
- From the Tornado diagrams, it can generally be concluded that those parameters which are related to “load” such as MG and Mass are more important than those parameters which are related to “strength” of structures.
-As Tornado diagrams show, the effect of Modulus of Elasticity (E) and Inertia Coefficient (C_M) can be ignored in investigating the ultimate behaviour of structures.

- From the table 3 to table 8, Collapse behaviour of structures is highly dependent on the value of random variables. For example:
-The results of this study can well be used for scoring and weighting in qualitative risk assessment of existing platforms.

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