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PROBABILITY OF FAILURE OF MONOPILE FOUNDATIONS BASED ON LABORATORY MEASUREMENTS

TIAGO FAZERES-FERRADOSA[1], FRANCISCO TAVEIRA-PINTO[2], RICHARD SIMONS[3], MARIA TERESA REIS[4], LUCIANA DAS NEVES[5]

1 Faculty of Engineering of University of Porto, Portugal, dec12008@fe.up.pt

2 Faculty of Engineering of University of Porto, Portugal, fpinto@fe.up.pt

3 University College London, United Kingdom, r.r.simons@ucl.ac.uk

4 National Laboratory for Civil Engineering, Portugal, treis@lnec.pt

5 International Marine & Dredging Consultants, Belgium, and Faculty of Engineering of University of Porto, Portugal, lpneves@fe.up.pt

ABSTRACT

Monopile foundations are in the lead as the most common offshore substructure worldwide. Therefore, the study of their behaviour and the optimisation of their design represent important contributions, for the development of the offshore wind sector. In order to optimise the design process of monopiles in the marine environment, it is important to account for the uncertainties that can affect these structures, namely those relating to scour phenomena and the means of scour protection. Uncertainty relating to scour can be handled by means of statistical approaches. Probabilistic design methods may enable the optimisation of design procedures.

This paper combines several results from physical modelling of scour development and a probabilistic model has been applied and extended to obtain probabilities of failure for the monopiles tested. This investigation will be used for comparison and calibration of the next phase of research, with a similar probabilistic approach being extended for waves and currents combined. The results presented are also used to provide an insight into future research concerning the failure of scour protection schemes. The relationship between safety factors and probabilities of failure of the monopiles is also presented.

KEWORDS: Monopile Foundations, Scour, Probability of Failure, Safety Factor, Monte Carlo

1 INTRODUCTION

Monopiles are commonly employed as part of the foundations for offshore wind turbines (Sørensen and Ibsen, 2013). According to the European Wind Energy Association (EWEA, 2015) the study of their behaviour and the optimisation of their design represent important contributions to the development of the offshore wind sector. The design standards and recommended practices for these foundations, provided by organizations such as Det Norske Veritas (DNV) and the International Organization for Standardization (ISO), are often conservative. This becomes evident, for instance, in cases where no scour protection has been applied (Sørensen and Ibsen, 2013).

In order to optimise the design process of monopiles in the marine environment, it is important to account for the uncertainties that can affect these structures, namely those relating to scour phenomena and their means of protection (Negro *et al.*, 2014). Similarly to other phenomena, the uncertainty relating to scour can be handled by means of statistical approaches. Probabilistic design methods may enable the optimisation of design procedures, with a measure of the reliability of the foundation, i.e. through the concepts of a reliability index or a probability of failure. These concepts can be used to quantify the uncertainties associated with the basic random variables of the phenomena and the semi-empirical theories of scour prediction.

The research concerning probabilities of failure induced by scour started with the work of Johnson (1992), in which a reliability-based approach was applied to pier scour in a river environment. More recently, other works have been performed, mainly for fluvial conditions and bridge-piers design, e.g. Bolduc (2006), Muzzammil & Siddiqui (2009), Briaud *et al.* (2014). However, for offshore monopile foundations, i.e. those installed in the marine environment, few studies based on probabilistic approaches can be found. Although the notion of a safety factor might be applied, it is rarely interpreted as a probability of failure. The definition of a failure criterion is a major issue in reliability based analysis. Failure criteria still offer an important area of study when searching for a suitable performance function to determine the probability of failure.

This research addresses a series of physical model tests regarding scour around cylindrical monopiles, under unidirectional current [Chee (1982), Chiew (1984)] for waves alone [Sumer *et al.* (1992)], and for scour protections under waves and currents combined [De Vos *et al.* (2011)].

The prediction model developed by Johnson (1992) was applied and extended to obtain updated probabilities of failure for the tested monopiles. The results presented in this report are also used to provide an insight into the future research direction. The relationship between safety factors and probabilities of failure of the monopiles is analysed and extended from Johnson's (1992) work. Moreover this methodology was applied and combined with adequate failure/safety criteria for a monopile in marine environment, with typical conditions of the North Sea. New results were also obtained for a model of a static scour protection typically employed in offshore windfarms.

The computation of probabilities of failure in scour protection was performed and analysed as a tool to be used for reliability and risk analysis applied to monopiles protected with rip-rap systems. The results show a comparison between the values of the probabilities of failure for independent random variables. A review of Johnson (1992) and Muzzammil & Siddiqui (2009) was performed for current alone, comparing the results achieved with Monte Carlo simulations and the First Order Reliability Method (FORM). A similar approach was used to develop different probabilistic models for offshore monopiles and offshore scour protections.

2 METHODOLOGY & DATA

The research was divided into three categories, according to the physical modelling tests and their flow conditions:

a) Current alone; b) Wave Alone; c) Scour Protections in the marine environment (waves + currents).

A full description of the data used to build the probabilistic models for each category can be found respectively in: a) Chee (1992), Chiew (1984) (compiled in Johnson (1992)), b) Sumer *et al.* (1992) and c) De Vos *et al.* (2011). For a deeper knowledge of the conditions in which the measurements were performed a review of these works is advised. All series of tests refer to scour depths measurements for cylindrical monopiles.

The methodology applied consisted of the following steps:

- Determine the random variables that rule the phenomena and describe them by means of statistical parameters;
- Obtain a suitable equation to describe the phenomena and create the future probabilistic model;
- Proceed with the random number generation, applying the Monte Carlo simulation algorithm;
- Determine a suitable failure criterion of the system and define the performance function *g*;
- Simulate the performance function;
- Obtain the probability of failure defined as *Pf = nº of failures/nº of simulations*;
- Determine the relationship between the probability of failure and a pre-defined level of safety (safety factor).

2.1 Random Variables and Random Generation

The scour phenomenon is very complex and the variables encompassed in it are stochastic in nature. Therefore it is important to treat them in a statistic manner that enables a quantification of the level of uncertainty present. The means and standard deviations were computed for each data base, in order to generate the random variables, according to the established probability distribution functions (PDF). The values of means and standard deviations will be presented in the case studies shown in the results.

It is important to note that the various probability density functions (PDFs) applied were either consistent with previous research performed, or assumed according the conclusions of such works. In future developments, a deeper study of the distributions applicable to the scour phenomenon would allow a better precision in the calculation of *Pf*. The research concerning the choice of PDF should be focused on complex statistic tools, such as sampling methods and hypothesis tests, which were not the aim of this investigation. Nevertheless, Chang (1994) presented Kolmogorov-Smirnov test results for several variables from category a), while applying normal, log-normal and Weibull distributions.

Table 1 summarizes the random variables studied. This table also includes the distribution used for further application of Monte Carlo Method and the justification for the assumptions made in the cases where no prior distribution was available. Except for water depth and the sediment uniformity parameter, the variables considered in category c) - data base concerning scour protections in the marine environment – were assumed to be normal in order to provide a conservative estimate of the probability of failure, ensuring a higher level of safety for design purposes. For the same reason, the correlation between variables was neglected. However some of the authors presented results of the correlation effect on the probabilities of failure, concluding that it leads to lower values of P_f (Chang, 1994). This research only considered independent variables. Further investigation is needed to assess the correlation's influence in categories b) and c).

Table 1 - Random variables and respective probability distribution function. Sources: 1 - Johnson (1992); 2 - Muzzammil & Siddiqui (2009); 3 - Assumed in a conservative and safety perspective. Note: λ = (observed scour depth)/(predicted scour depth).

Variable	Category	Source	Distribution (PDF)	Justification
Water depth (y)	a); b); c)	1	Normal	Consistent with the sources.
Model correction factor (λ)	a); b)	1	Normal	
Pier with (b = cylindrical pile diameter)	a)	2	Constant	
Pier depth (d_p)	a)	2	Normal	
Sediment uniformity parameter (σ_s)	a); b); c)	1	Log-normal	
Froude's number (F_r)	a)	1	Log-normal	
Pile diameter (D_p)	b)	1	Normal	According Chang (1994), Muzzammil & Siddiqui (2009) – normal distributions yield a conservative estimate for *Pf*. Weibull was used to seek extreme velocity values near storm situation.
Nominal mean diameter ($Dn_{50}=0.84D_{50}$)	c)	3	Normal	
Significant wave period (T_s)	b) c)	3	Normal	
Significant wave height(H_s)	c)	3	Normal	
Maximum flow velocity (U_m)	c)	3	Weibull	
Current velocity (U_c)	c)	3	Normal	

2.2 Probabilistic Models

a) Current Alone

The probabilistic model used for Chiew (1984) and Chee (1982) data base was based in the Colorado State University Equation (CSU - Chase & Holnbeck, 2004). Johnson's modified pier scour model was fitted by means of the non-linear least squares method, through MATLAB. This technique was similarly applied in Johnson's (1992), Chang (1994) and Muzzammil & Siddiqui (2009).

$$g = d_p - \lambda \times \left(c_1 \times y \times \left(\frac{b}{y} \right)^{c_2} \times F_R^{\,c_3} \times \sigma^{c_4} \right) \tag{1}$$

By generating the values of the random variables, according the PDFs in Table 1, it is possible to predict the associated scour depth, D_S, which can be used as the input to the safety criteria (performance function) that leads to *Pf*.

b) Waves Alone

The equation applied to obtain a scour depth estimate (D_S), in wave conditions was that proposed by Sumer (1992); this formulation was developed from the same data base as the one applied in the present research.

The equation is mainly based on the influence of KC on scour depth. Since this equation directly considers the values of KC, it is important to simulate the random stochastic behaviour of the variables used to obtain it. Sumer's equation is presented as follows, where D_s is the predicted scour depth:

$$Ds = \left(1.3 \times \left\{1 - \exp\left[-m \times \left(KC - 6\right)\right]\right\}\right) D_p \tag{2}$$

$$KC = \frac{\left(U_m \times T\right)}{D_p} \tag{3}$$

By definition equation (2) states that the maximum scour depth corresponds to 1.3 times the pile diameter (DNV, 2013). The fitting coefficient *m* was obtained by means of the non-linear least square methods.

The tests concerning the current flume in Sumer's data base (1992) were not analysed since the values of KC tend to infinite, hence producing non-realistic values of the new generated values of KC.

Also the experiments with no scour depth outcome were removed from the data base, in order to respect the limits of equation (2) which is recommended for KC>6. The overall removed cases corresponded to run numbers: 1, 2, 3, 25, 26, 27, 38, 50, 51, 52, 53. Besides those, a total of 42 experiments were used for the generation of random variables and the construction of the probabilistic model.

c) Scour protections in marine environment – waves and currents combined

To build the model for the scour protection cases, the data base presented by De Vos (2011) was studied and the analysis was performed in terms of the critical shear stress (τ_{cr}) values at the top layer of the protection. De Vos (2011) presented a dimensional equation to predict τ_{cr}. This equation was derived from regression analysis applied to the laboratory measurements of the shear stress caused by currents (τ_c) and waves (τ_w).

Equation (4) presents a version of the De Vos (2011) formulation applicable for prototype scale. τ_{crPred} corresponds to the predicted shear stress values. Note that this equation also depends on the sediment properties and other variables. For a detailed account the reader is referred to De Vos (2011).

$$\tau_{cr\,Pred} = 83 + 3.569 \times \tau_c + 0.765 \times \tau_w \tag{4}$$

2.3 Performance Functions, Failure Criteria, and Safety Factors

a) Current Alone

A similar failure criteria as the one in Johnson (1992) and Muzzammil & Siddiqui (2009) for currents alone was applied, in order to validate the magnitude of results obtained for each P_f. In this case, it is considered that the monopile fails if scour depth D_S exceeds pile depth (d_p), i.e. the length of the pile buried into the foundation soil.

Therefore a safety margin, which is commonly adopted as the performance function of the monopile, can be defined as:

$$M = g(x) = d_p - \lambda \times D_S \tag{5}$$

To incorporate the model structure uncertainty, the model correction factor ($\lambda = D_{Sobserved}/D_{spredicted}$) was applied to the equation as in the research mentioned above and the concepts presented by Ang & Tang, 1984. Note that when $g(x)<0$ the monopile is considered to have collapsed. The final formulation of $g(x)$ for current alone, using the non-linear least squares method to compute c_i, is the following (c_i values are already in this equation and are presented in table 2):

$$g = d_p - \lambda \times \left(1.36 \times y \times \left(\frac{b}{y} \right)^{0.74} \times F_R^{\ 0.16} \times \sigma^{-0.22} \right) \tag{6}$$

Another possibility to analyse the collapse or failure situation is the alternative formulation of $g(x)$, the so-called safety factor (SF). In this perspective g corresponds to the ratio of resistances over loads, which in this case is the ratio between the pier depth and the predicted scour depth. If a certain situation is associated to $SF<1$, it means that failure occurs because d_p is exceeded by the scour depth:

$$SF = \frac{d_p}{\lambda \times \left(1.36 \times y \times \left(\frac{b}{y} \right)^{0.74} \times F_R^{\ 0.16} \times \sigma^{-0.22} \right)} \tag{7}$$

b) Waves Alone

The failure criterion has a considerable impact in P_f values [Fazeres-Ferradosa & Taveira-Pinto (2015)]. Design of offshore foundations is often governed by serviceability criteria, where top-mass displacements must be controlled, and fatigue limit state, which obliges to control the natural frequency of the structure, where resonance effects must be avoided.

Recently Prendergast (2015) conducted a physical modelling study concerning scour effects on the natural frequency of an offshore windfarm. This research concluded that for a model of a monopile with an external diameter of 0.34 m and a scour depth of 1.66D_p, in loose, medium dense and very dense sand, could lead to a reduction in the natural frequency ranging from 8.5% to 12.5% of the values presented for $D_s=0$, which can affect the soft-stiff design typically employed in this structures.

Sørensen & Ibsen (2013) reported smaller changes in the natural frequency, around 5%. However this could be because they considered the API approach to determine the small-strain shear modulus of the soil, leading to different stiffness profiles. As a result, the material lost at the top layers of the soil had a smaller effect on the natural frequency of the structure.

Based on the effects of scour on the natural frequency of monopiles, a possible example of a failure criterion was defined. In this example it is assumed that the soil stiffness profile has its own uncertainty and therefore the natural frequency will be controlled by limiting the scour depth to a maximum of 1.1D_p, which corresponds to changes in the natural frequency from 6% to 8%, depending on the stiffness of the soil. The concepts of λ and SF are adapted from Johnson (1992). In Sumer's equation to predict D_S the fitting coefficient m is obtained by the non-linear least squares method. In the present work it is found to be equal to 0.0188, while Sumer (1992) presented a value of 0.03. If $g<0$ or alternatively if SF<1, the changes in the natural frequency overcome the established limits and the system is considered to have failed.

$$g = 1.1D_p - \lambda \times \left(1.3 \times \left\{1 - \exp\left[-0.0188 \times (KC - 6)\right]\right\}\right) D_p \tag{8}$$

$$SF = \frac{1.1D_p}{\lambda \times \left(1.3 \times \left\{1 - \exp\left[-0.0188 \times (KC - 6)\right]\right\}\right) D_p} \tag{9}$$

c) Scour protections in marine environment – waves and currents combined

Scour protection is commonly designed on the basis of the mean stone size, D_{50}, required to resist the critical shear stress in the vicinity of the pile. Usually the conditions for the threshold of motion are assessed and then the top layer is designed based on the assessment made. Every time the critical bed shear stress used for design purposes is underestimated, the protection might fail. In this sense, the formulation presented by De Vos (2011) in equation (4) is compared with the critical shear stress at the top layer defined according Shields parameter (θ_{cr}), referred to as $D_{67.5}$, as in De Vos (2011). The failure criterion is established according equation (10), where ρ_w is the density of water, s is the relative density of the stones (ρ_s/ρ_w), g is the gravitational accelerationand θ_{cr} equals 0.035 as in the research cited above (De Vos, 2011). In this case no value of model correction factor was applied, since there was no evidence that such an application could improve the prediction model. This could be due to the fact that the data in De Vos (2011) covered only a small range of D_{50}.

$$g = \tau_{cr\,Pred} - \tau_{cr\theta} = (83 + 3.569 \times \tau_c + 0.765 \times \tau_w) - \frac{\theta_{cr}}{\rho_w \times g \times (s-1) \times D_{67.5}} \tag{10}$$

$$SF = \frac{\tau_{cr\,Pred}}{\tau_{cr\theta}} = \frac{(83 + 3.569 \times \tau_c + 0.765 \times \tau_w)}{\dfrac{\theta_{cr}}{\rho_w \times g \times (s-1) \times D_{67.5}}} \tag{11}$$

If g<0 it means that the design established according the predicted stress (τ_{crPred}) led to a D_{50} that is not large enough to resist the critical shear stress around the pile, given by $\tau_{cr\theta}$. The same interpretation can be made for SF<1.

2.4 Probability of Failure, Simulations and Probabilistic Convergence

The probabilities of failure were computed using Monte Carlo simulations according equation (12).

$$P_f = \frac{n^o (g < 0)}{N} \tag{12}$$

N corresponds to the number of simulations performed. Independence was assumed as justified in table 1. It is important to stress that future studies should investigate the effect of correlations among variables on P_f. Probabilistic convergence was achieved by the Latin Hypercube Algorithm (Shields & Zhang, 2016). For each failure criteria the probabilities were plotted against the sampling length. The plot shows that final samples were large enough to reach probabilistic convergence. Results showed a stabilization of P_f lower than 0.02%. The x-axis is in log-scale.

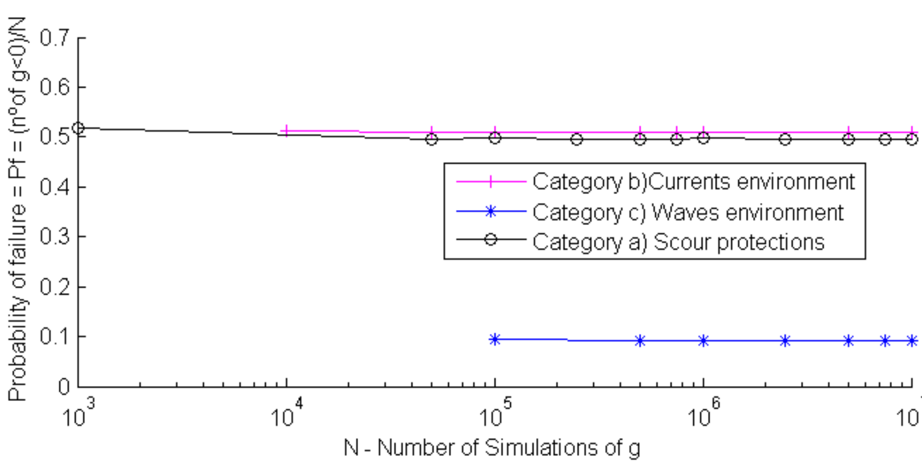

Figure 1 – Convergence of the probabilities of failure for each category studied.

3 RESULTS ANALYSIS AND DISCUSSION

3.1 Currents Alone – Category a) – Johnson (1992) and Muzzammil & Siddiqui (2009) revisited.

The coefficients c1, c2, c3 and c4 are compared in the following table. These coefficients correspond to the fit made using a method of nonlinear least square, as applied in Johnson (1992) and Muzzammil & Siddiqui (2009). The c_i coefficients are the ones that allow equation 1 to become equation 6:

Table 2 – non-linear least-squares' results for c_i.

Equation inputs	Johnson (1992)	Muzzammil & Siddiqui (2009)	Present (Eq. 6)
c_1	2.02	1.40	1.36
c_2	0.98	0.72	0.74
c_3	0.21	0.22	0.16
c_4	-0.24	-0.27	-0.22

The present coefficients were calibrated for 75% of the data base (Figure 2 – red circular markers) and the other 25% were used for validation purposes (Figure 2 – blue cross markers), as in the same procedure used in Muzzammil & Siddiqui (2009). The efficiency of algorithms used in this research is indeed more powerful than the ones available in 1992. This fact justifies the differences between the fits from Johnson and the most recent ones; nor did Johnson divide the data into calibration and validation cases. Johnson's fit was applied to the total of 130 scour experiments.

The differences presented between this work and Muzzammil & Siddiqui (2009) aren't very significant. However the differences might be because: i) Muzzammil & Siddiqui (2009) only used 109 points of 130 available, stating that outliers larger than 3 standard deviations were removed. In this case the 130 cases were used. It was considered that scour is an extreme phenomenon and therefore a more realistic approach would be to consider all data at once; ii) There is no specific indication of which tests were used for the calibration (75% cases) and validation (25% cases) in Muzzammil & Siddiqui (2009). This validation was performed using tests cases 5 to 10, 14 to 22, 53 to 57, 90 to 98 and 125 to 127. Therefore slight changes might be reflected in the coefficients c_i, which according to the previous table do not seem to be very significant.

Nevertheless, the magnitude of the coefficients is very similar for all authors. The three models were plotted and their correlation coefficients were computed, between predicted scour depths and the observed values of Chiew (1984) and Chee (1982). Figure 2 shows that reasonable agreement was achieved for the c_i coefficients, with a good match between observed and predicted values. The cases with higher values of scour depth indicated greater deviations from the 45º line, which also happened in the other two models. The reasons for such ebehaviour are explained in Johnson (1992) (see Figure 3).

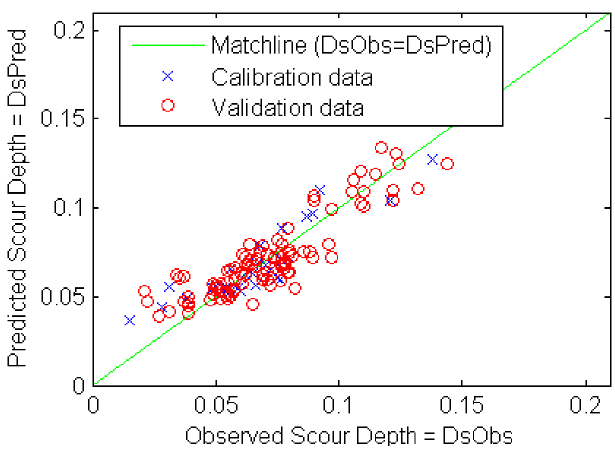

Figure 2 – calibration and validation of CSU equation.

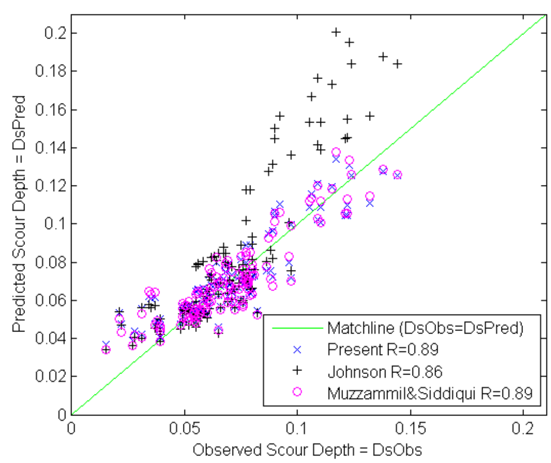

Figure 3 – comparison of predictions between studies.

Table 3 shows considerable differences in P_f values for SF>1.6. These differences could be due to the c_i values used in g. However, the Monte Carlo method was applied for Muzzammil & Siddiqui (2009) coefficients and the results obtained are outlined in red (table 3), which are much closer to the present study that the ones from 2009. The values of μ and s were defined as in Muzzammil & Siddiqui (2009).

The minimum number of simulations (N) required to obtain a consistent P_f=6x10^{-5} was calculated through DNV recommendations (DNV, 1992) and Broding (1964). For a confidence level of 95%, N was respectively equal to 1 666 700 and 49 929 simulations. The present study conducted 10 000 000 simulations in category a), which is considerably more than used in Muzzammil and Siddiqui (2009).

Table 3 – Probabilities of failure and safety factors for category a) currents. μ=mean and s=standard deviation . SI units.

SF	Pf Present	Pf Muzzammil & Siddiqui (2009)	Application Case	μ	s
1	0.4845	0,5	y	4.25	0.85
1,1	0.3112	0,31	b (constant)	2	-
1,2	0.1893	0,17	d_p	2.16	0.0216
1,3	0.1119	0,087	λ	1	0.18
1,4	0.0655	0,039	F_r	0.54	0.2052
1,5	0.0384	0,016	σ	4	0.8
1,6	0.0229	0,006	0.0439	Pf obtained with Muzzammil's c_i values and Monte Carlo Method instead of FORM	
1,7	0.0139	0,0021	0.0273		
1,8	0.0086	0,0012	0.0172		
1,9	0.0054	0,00066	0.0110		
2	0.0035	0,00006	0.0071		

This leads to the conclusion that the FORM method applied in previous studies did not give consistent results when compared to the Monte Carlo employed in the present research. FORM underestimated the probabilities of failure for independent variables in this application case. This might be caused by the linearization implied in FORM and by the fact that FORM assumes that all variables follow a normal distribution. Note that σ and Fr were considered to be log-normal distributions.

Nevertheless, arriving at similar conclusions to those outlined in previous studies, the method presented in the current research confirms that safety factors should be used carefully and a probabilistic measure of failure should always be calculated when analysing collapse situations caused by scour phenomena. This notion becomes evident when we associate to each value of *SF* the correspondent failure probability. For example, if SF=1.3 we would think that the buried length of the pile should be enough to resist a scour depth with 130% of its dimensions. However as it can be noticed for SF=1.3 there is a probability of failure, i.e. a probability of collapse, equal to 11.19%, which might be unacceptable for design purposes.

3.2 Waves Alone

A fit was made to Sumer's (1992) database and a coefficient m= 0.0188 was obtained. The following figure compares both models. The present method gives a slight improvement from the previous one and was used as a best fit model to obtain P_f.

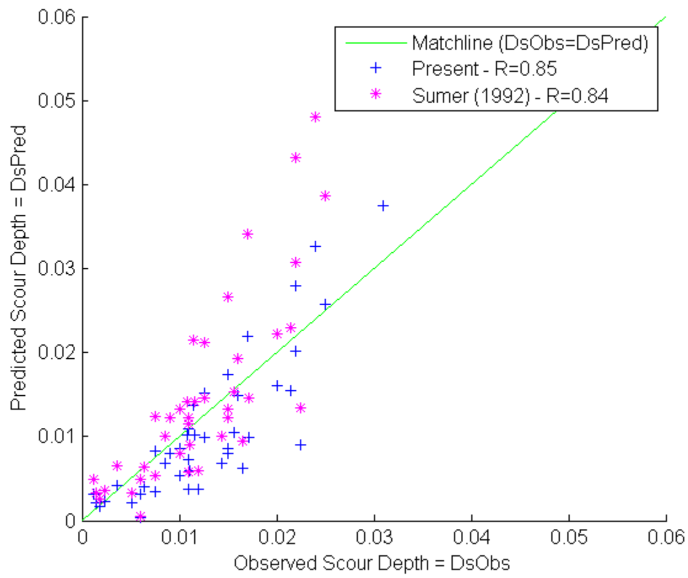

Figure 4 – Fit used to establish the prediction of scour depth. Present study m=0.0188; Sumer (1992) m=0.03.

Table 4 – Probabilities of failure vs. Safety Factors for an Offshore monopile.

SF	Pf Present	Application case	μ	s
1	0.4904	D_p	4	0.04
1,1	0.4558	KC	50	25
1,2	0.4254	λ	1.7	1.9
1,3	0.3992	KC values were defined to force the existence of failure situation, for a monopile with diameter of 4 m.		
1,4	0.3758			
1,5	0.3548			
1,6	0.3363			
1,7	0.3196			
1,8	0.3045			
1,9	0.2908			
2	0.2784			

Although higher than 6, Sumer's data base presented very low values of *KC*. Therefore while generating values of H_s (with μ =[6.5;10] m and *s*=[0.2;0.5]), U_m (with μ =[1.5;4] m/s and *s*=[0.7;1.5]), and T_s (μ =[11;22] s and *s*=[1.5;4] s) it was not possible to reach a suitable failure sampling. For the failure criteria presented before, KC values should be much higher. This suggests the following possibilities: i) the failure criteria might have been too restrictive, implying a very high number of simulations, which wouldn't be feasible to run until failure occurs; ii) Sumer's data base might have led to very low values of U_m and T_s during the random variables generation, resulting in very low KC numbers and no failure occurrences. This could be solved by increasing the sample used for the generation; iii) the distributions applied for Monte Carlo method do not represent the behaviour of the variables in a suitable way, hence suggesting that their definition should be checked. In future studies, a Weibull distribution applied to U_m and T_s and a Rayleigh distribution in H_s should be analysed to see if they provide a better description of the sea state that can lead to failure. In table 4, μ and *s* were defined for typical storm conditions in North Sea.

In order to illustrate the application of Johnson's (1992) methodology to the present case, KC was directly simulated through a Weibull distribution, with μ=50 and *s*=25, for a monopile with D_p= 4 m. Note that P_f values must be carefully interpreted since the randomness of the process relies on U_m, T_s and H_s, which were not used in this part of the application. The distribution, mean and standard deviation of KC were chosen to represent a typical extreme situation, where the number of simulations near failure could be increased. These values serve merely as an example: the future steps of this research will be focused on: 1) increasing the experimental data base, 2) the PDFs' analysis and 3) the design application for real prototypes. The values of P_f and associated *SF* for this situation are presented in table 4. In this case the uncertainty associated with the global safety factors is naturally high. For example, designing for a *SF*=1.5 will not respect the natural frequency *vs.* scour depth criteria, defined in section 2, in 35.48% of the times, which was expected since the assumptions were done to be in a "near failure situation". The present study recommends a deeper investigation into other failure criteria and the distributions used for random variables generation.

3.3 Scour Protection in the marine environment – Category b) De Vos (2011)

Applying the same procedure used in the previous categories to the scour protection, with the failure criteria defined in section 2, similar values of P_f can be associated to safety factors. Table 5 summarizes the application case and the probabilities of failure for each *SF*.

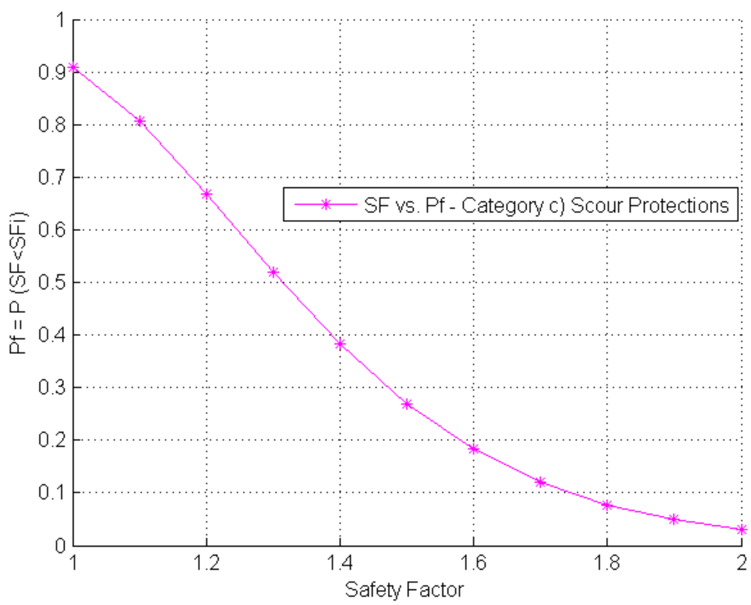

Figure 5 – Probabilities *vs.* failure and Safety Factors.

Table 5 – Probabilities of failure vs. Safety Factors - Scour Protection in marine environment. SI units.

SF	Pf Present	Application case		
		-	μ	s
1	0.9090	y	20	0.5
1,1	0.8077	Dn	0.3	0.05
1,2	0.6690	T	11.2	3
1,3	0.5197	Uc	2	0.7
1,4	0.3824	H	6.5	0.5
1,5	0.2692	θ_{cr}	0.035	-
1,6	0.1827	ρ_w	1000	-
1,7	0.1204	P_s	2650	-
1,8	0.0776	$D_{67.5}$	0.32	0.07
1,9	0.0492	-	-	-
2	0.0308	-	-	-

Figure 5 shows the outputs from Table 5, where μ and *s* were defined based on De Vos (2011) values, which are typical for the North Sea. As can be seen, for a scour protection in typical offshore conditions, if the safety factor is assumed to be 1, i.e. $\tau_{crPred} = \tau_{cr}$, with D_{50}=0.3 m, the protection is very likely to fail since, for the assumptions made, *SF* will be less than 1 for 90.9% of the time. However, when designing for a SF higher than 2 the failure of protection will most likely occur in approximately for 3% of the time. This process enables the association of a certain D_{50} to a pre-determined P_f.

By reversing the process an optimised scour protection can be designed. For instance, if the requirement was to decrease P_f from 3% to 0.5% for the same sea state conditions and Shields parameter, the new safety factor associated would be SF=2= $\tau_{crPred}/\tau_{cr\theta}$.

Including the new *SF* in the failure criterion defined in equation (11) and noting that the shear stresses for waves and currents depend on D_{50} and are computed as in De Vos (2011) a new stone size D_{50}=0.4 m is obtained.

Future work is being developed for dynamic scour protection systems where some extent of movement of the rock protection is allowed. This would imply a less restrictive criterion in terms of shear stress or the area of filter layer exposed.

4 CONCLUSIONS

The present work establishes the basis to perform a quantitative comparison of the risk of collapse in offshore monopiles and offshore rip-rap scour protection systems. The best fit models applied to the three categories allow an optimisation of the structure, by leading to less conservative values of scour depth. The required design dimensions of the structure can be defined according to the safety factor previously determined from the acceptable probability of failure. Future studies should increase the number of simulations for categories b) and c), which were limited by the wave length calculation. It would also be important to analyse the effects of correlation between variables for the application cases presented.

This study extends the method presented in Johnson (1992) for scour phenomena to cases under the action of waves and to scour protection under the action of combined waves and currents. The relationship between safety factors and probability of failure has been established successfully for the three types of events and examples of new failure criteria have been suggested for categories b) and c). Latin Hypercube Sampling was successfully used to reduce the number of simulations needed. For current alone cases, this study predicts higher values for probability of failure when compared to the FORM method applied in Muzzammil & Siddiqui (2009). This research contributes to the probabilistic assessment of uncertainty and to provide a measure of failure in scour protection systems, which can be further applied to safety design optimisation and the reduction of the material costs of the rip-rap stones.

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