VI International Conference on Computational Methods in Marine Engineering
MARINE 2015
F. Salvatore, R. Broglia and R. Muscari (Eds)

FATIGUE ANALYSIS OF AN OFFSHORE WIND TURBINE IN MEDITERRANEAN SEA UNDER A PROBABILISTIC FRAMEWORK

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Keywords: Offshore Wind Turbine, Monopile Design, Fatigue, Mediterranean Sea

Abstract. Wind Turbines constitute a sustainable and effective solution for the production of energy using wind power. Offshore wind turbines especially are becoming of special interest. However, their design poses great challenges, since an offshore structure is subject to combined wind and wave dynamic loading that is characteristic of the site of installation. The purpose of this paper is to provide a case study of fatigue life assessment for the cross-section at mudline (foundation) of a standard offshore wind turbine with a monopile design, under a probabilistic framework and assuming the diameter and thickness of the examined cross-section as the design variables. Two potential sites of construction in the Aegean Sea of Greece (part of Mediterranean Sea) were examined. A probabilistic approach was employed in order to determine the fatigue life based on anemological data at each of the two sites of interest. At its basis is an extensive Monte Carlo simulation of wind (velocity) and wave (height, period) characteristics. The results show the dependence of fatigue life on the local wind and wave conditions, the cross-section size (e.g. diameter and thickness of the foundation's pile) and the welded connection detail. All in all, the more benign conditions in the Aegean allow simpler connection details and smaller in size cross-section of foundation pile's cross-section to still have acceptable performance.

1 INTRODUCTION

Wind turbines constitute a sustainable and effective solution for the production of energy using wind power. Wind turbines may be constructed either in land areas (onshore) or in sea areas (offshore). Offshore wind turbines are becoming of special interest in recent years. Although an offshore wind turbine usually starts with a higher initial cost, it can outweigh a similar onshore one during its service life in a number of aspects such as: higher productivity due to stronger winds over sea areas, larger available installation areas and lower (or even non-existent) public nuisance. The latter is especially important in countries such as Greece where protracted court battles have hindered most onshore wind farms, inflicting substantial cost and crippling delays.

A wind turbine could be considered as a structure that lies between a civil engineering structure and a machine [1]. In specific, a wind turbine consists of structural elements (tower, substructure etc.) and a number of electrical and machine components with a control system (gear box, drivetrain etc.). Under a civil engineering perspective, the main components of a wind turbine could be considered the tower and the substructure system. The tower is the element on the top of which the mechanical parts of the wind turbine, such as the nacelle and the blades, are installed. The tower is made of steel and has a circular cross-section. It is usually tapered i.e. the cross-section size (e.g. diameter, thickness etc.) decreases with height, typically in a linear fashion. The tower is connected to the substructure, i.e., the part of the wind turbine that is submerged in the water. The substructure may be founded directly in the seabed or based on a floating platform. This type of the substructure's foundation usually distinguishes an offshore wind turbine into two categories, namely fixed and floating. Fixed wind turbines are used especially in sites of low or medium depths, while the construction of a floating wind turbine is cost-effective in the case of deep waters. The most common type of design for fixed wind turbines, which is used for depths up to 30 meters, is the monopile. This is probably the simplest structural concept, where the tower is connected (directly or via a transition piece) to a pile that has been founded at the seabed.

Regardless of the type of an offshore wind turbine, both structure and substructure are subject to dynamic combinations of wind and wave loads with a wide range of frequencies. This fact may raise critical issues during the turbine's service life in terms of fatigue and power efficiency [2]. For this reason, special focus should be devoted on the appropriate analysis and assessment of the dynamic combination of loads during the design phase. Furthermore, since wind turbines are complicated structures including a number of different components, reliability analysis considering consistent reliability levels and taking into account the dynamic nature of loads has received considerable attention by researchers [1, 3]. However, a great challenge in the above analysis is posed by the stochastic nature of the main loading mechanisms, namely wind and wave, as their characteristics tend to vary rapidly. Their stochasticity mainly depends on the climate at the area of construction. Thus, one could say that the design of an offshore wind turbine is a highly site-specific process. For this reason, the use of accurate site anemological and wave data is essential.

As far as the loads are concerned, the aforementioned stochasticity affects their magnitude and also subjects the structure to cyclic stresses making its components vulnerable to fatigue damage. Furthermore, they affect the overall performance and energy output. Research efforts are currently under way to incorporate climate information and relate it directly to the calculation of fatigue damage [4] or the assessment of performance [5]. However the stochastic nature of the wind and waves, as physical phenomena, makes such an analysis very complicated and advanced methods from statistics and probability theory need to be incorporated.

The purpose of this paper is to provide case studies of a probabilistic fatigue life assessment for a standard offshore wind turbine located in the Aegean Sea of Greece, which constitutes the eastern part of Mediterranean Sea. In specific, a fixed offshore wind turbine with a monopile foundation is studied. Two potential sites of construction, one in the north part and another in the south part of Aegean, with different wind and wave characteristics, are considered. For both sites dynamic loading analysis is performed and the corresponding fatigue damage of the pile's cross-section at the mudline of the structure is calculated for different wind-wave states. The estimation of the expected fatigue life is made by incorporating Monte Carlo simulation. Furthermore, the diameter and the thickness (i.e. the size) of the cross-section are examined as design variables. In specific, estimations of the expected fatigue annual damage and corresponding life are made, for two potential values of diameter and a range of values of thickness, and inferences about the influence of these parameters to fatigue life are made for both sites.

2 THE WIND TURBINE MODEL

The National Renewable Energy Laboratory (NREL) 5MW Baseline Wind Turbine was selected as a standard offshore wind turbine for this study. The rated power is 5 MW. The tower of the turbine is tapered and of steel circular hollow cross-section. The base diameter is 6.00 m and the thickness 27 mm, while the top diameter is 3.87 m with a thickness of 19 mm. The height of the tower at its top point (where the nacelle is based) is at 87.60 m from the Mean Sea Level (MSL). The rotor has three blades. The rotor disk has a diameter of 126.00 m and its center (hub height) is located at 90.00 m from the MSL. The cut-in and cut-out wind speeds are 3 m/s and 25 m/s respectively. For additional details regarding the characteristics of the standard turbine the reader may refer to [6]. The tower is connected to a monopile foundation via a transition piece (TP). The monopile is considered to be founded at a depth of 28 m. It has a steel circular hollow cross-section, 6.00 m in diameter. The thickness of the pile's cross-section in the standard model is 60 mm. The connection of the base of the tower to the transition piece is considered to be at 10.00 m of the MSL. Finally, a rigid type of foundation is assumed.

3 THEORETICAL BACKGROUND

Design criteria and analysis guidance are provided by published standards. The analysis of offshore wind turbines is mainly based on the IEC 61400-3 standard [7]. It specifies the context for the assessment of external conditions and the design requirements to ensure the engineering integrity of the structure. The IEC standard also provides an appropriate level of protection from all hazards during the planned lifetime of an offshore wind turbine. In addition, the DNV standards [8] can also be used for the assessment of loads on marine structures subjected to wind, wave and current loading.

3.1 Loads

The assessment of wind loads is critical for the analysis of an offshore wind turbine. Although wind is essential for the operation and efficiency of a wind turbine, it is also the environmental factor with the greatest contribution to the loading of the structure. For the assessment of wind loads, time-series of wind speed at the hub height of the wind turbine are used. The time-series may have been developed according to specific spectrums (such as Kaimal or von Karman), based on the characteristic (average) value of a 10-minute wind speed. For this process appropriate software can be used, such as the TurbSim software developed by NREL [9] and adopted in this study. The wind time-series are then used as the input to calculate the values of reactions and deflections at the structure due to the wind. In this study, the authors used the FAST software [10].

Offshore wind turbines are also subject to wave loads which in some cases (e.g. in North Seas) may be very significant. Wave characteristics, such as the significant wave height (H_s) and peak spectral period (T_p), depend on the wind speed and the available sea length, or fetch, over which the wind transfers energy to the sea. Several methodologies and associated wave spectra are available for the calculation of the dynamic wave characteristics. A very widely used spectrum is JONSWAP [7, 8] that will also be our choice. A simplified method to transform wave characteristics into forces on a structure is the Morison equation [11]. This is a semi-empirical method for calculating the acting force on a body (e.g. a pile) that is submerged into moving water. For more details about the application of the Morison equation, the reader may refer to [7, 8].

3.2 Fatigue

Fatigue is considered as the damage in a member of a structure through crack initiation and/or crack propagation due to repeated stress fluctuations. Various standards have been published for the design of steel structures against fatigue. In the Eurocode series, part 1.9 of EC3 [12] provides the analysis context for fatigue design of steel structures. For the estimation of fatigue damage, time-series of stress history associated with the structural member of interest are needed. After those time-series are obtained, the stresses of various magnitudes should be grouped into groups of specific stress magnitude. Then, the number of cycles (i.e. the frequency) of each group is counted. A very widely used approach for counting the number of cycles is the rainflow counting algorithm [13, 14].

By incorporating rainflow counting, the number of cycles of stress is calculated for each of the different stress amplitudes (or groups). Once the number of cycles for each group is specified, the corresponding fatigue damage can be estimated. The total damage D in a stress history of a specific length is then calculated by the following formula (Palmgren-Miner rule):

$$D = \sum_{i=1}^{k} \frac{n_i}{N_{fi}} \tag{1}$$

where: n_i is the number of cycles observed for stress group i, and N_{fi} is the number of cycles to failure for stress group i.

The fatigue life of a structural member is the time until D reaches the maximum allowable value of 1. Assuming that D has been estimated for a representative enough interval of duration T_D over which its accumulation may be assumed to be stationary, a good estimate (assuming deterministic capacity) of the corresponding fatigue life is equal to T_D/D. For instance, if D is the mean annual fatigue damage of a member, the estimated fatigue life in years is equal to $1/D$ (in this case $T_D=1$).

4 CASE STUDIES FOR GREECE

4.1 Examined Sites

Offshore wind farms have been constructed and are in operation in the northern seas of Europe. On the other hand, none have been installed in the Mediterranean Sea. However, a number of projects are ongoing for examining the potential of design and installation of offshore wind farms by several Mediterranean countries [15]. In this paper, two case studies will be presented for the preliminary assessment of fatigue life for the cross-section at mudline of a standard offshore wind turbine with a monopile foundation, considering two different diameter values and a range of thickness values of the cross-section. In specific, two different sites in the Aegean Sea of Greece were selected, shown in the map of Figure 1. Each has its own wind and wave characteristics, in large part due to the difference in the surrounding geography. For the case of the North site, due to the proximity of the mainland, significant difference in fetch (i.e. the uninterrupted length of water over which waves can develop) exists for the various wind directions, with the maximum appearing for a southern wind. In the case of the South site though, no much difference could be assumed between the different directions and a practically uniform fetch could be used for the analysis.

Figure 1: Map of Aegean Sea with the examined installation sites

4.2 Analysis Process

For both sites of the study a similar process was followed for the estimation of the fatigue life. First, anemological data was obtained from the National Weather Service of Greece. Given the relatively small fetch distances in the Aegean, the wind speed is reasonably assumed to fully determine the wave state as well, something that would not be true, for example, in an ocean environment. Thus, the wave characteristics (significant wave height and peak period) were calculated based on the JONSWAP spectrum for each possible value of *local* wind speed. Finally, the joint probability density function (joint PDF) of wind speed (U) and significant wave height (H_s) were estimated, a process that will be discussed in more detail in the next section.

For the analysis of loads, time-series of wind speed at the hub height were simulated using the TurbSim software. In specific, time-series of 10-minute length, for a number of wind speed values, namely 3 m/s (cut-in), 5 m/s, 10 m/s, 15 m/s, 20 m/s, 25 m/s (cut-out) and 30 m/s (parked turbine) were developed. The aforementioned time-series along with the corresponding wave characteristics constituted the input for the FAST software, where a coupled dynamic analysis of wind and wave loads was performed.

A number of 10 simulations were performed for each mean wind speed. Based on those time-series, the 10-minute stress history, by incorporating the reaction forces and moments were calculated for the cross-section of interest. As far as the geometry of the cross-section is concerned, two different diameters, namely 5.50 m and 6.00 m, and values from the range between 25 mm to 60 mm (with a step of 5 mm) for the thickness were examined. Rainflow counting and the Palmgren-Miner rule were used for the calculation of the 10-minute fatigue damage. Two different classes of detail, namely 40 MPa and 71 MPa, were assumed for the welded connection and the corresponding S-N curves of EC3 part 1.9 were employed. According to EC3, a detail of 40 MPa corresponds to fillet welds, while a detail of 71 MPa corresponds to butt welds for connecting a circular hollow section to a ring-shaped flange plate.

From the above process, 10 potential values of 10-min fatigue damage were estimated for each of the selected wind speeds. Based on those 10 values the empirical cumulative density function of damage for each of the wind speeds was calculated and thus the empirical distribution of the damage was specified. For intermediate values of wind speed linear interpolation was used for determining the corresponding fatigue damage distribution.

The final step was to estimate the annual damage based on the 10-minute damage and the distribution of the annual wind speed data. Once the annual damage is calculated, the estimated fatigue life in years is equal to the reciprocal of that value. The process of calculating the annual damage (and the corresponding fatigue life) can be repeated numerous times since the distributions of the fatigue damage and the anemological data of the site are known. Thus, a Monte Carlo simulation for 100 years was performed in this study, in order to estimate (the distribution of) the fatigue life in the cross-section of interest. The results of this simulation for both sites and details of connection will be presented in the next section of the paper.

5 ANALYSIS RESULTS

5.1 Case 1: North Aegean Sea

The first site that was examined is in the north part of the Aegean Sea. The distribution of the 10 min mean wind speed at 10 m (U_{10}) of the MSL in a typical year is shown in Figure 2 (left graph). A statistical analysis also showed that the mean value of wind speed was 5.41 m/s and the standard deviation 2.92 m/s. Furthermore the distribution of the wind speed is best modeled by a lognormal distribution with parameters μ = 1.56 and σ = 0.51. Regarding the wind direction, North-East (24.6%) and North (12.9%) constitute the preferred directions of winds in a typical year. These directions though are associated with small fetch (6.0 Km and 5.8 Km, respectively), thus waves with low H_s and T_p are expected to dominate in the North site.

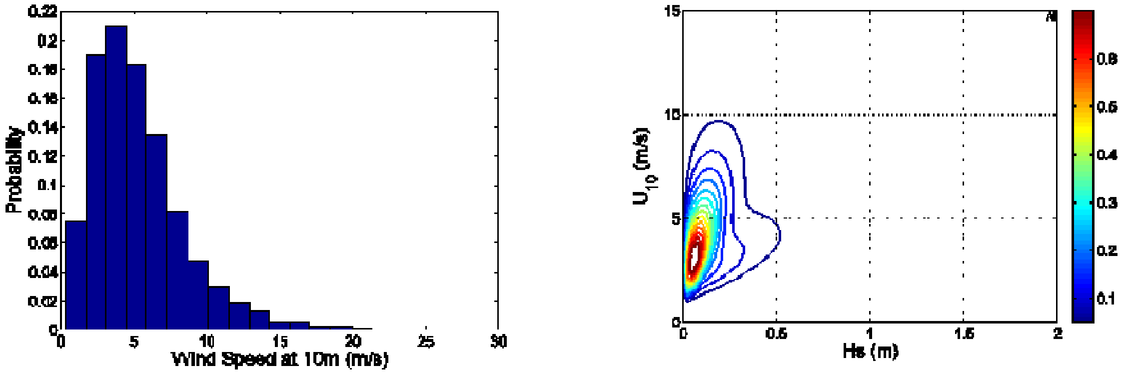

Figure 2: Distribution of non-zero 10 min mean wind speed at 10 m height for North site (left graph). Contour plot of the joint PDF $f(H_s,U_{10})$ (right graph)

The next step in the analysis was to estimate the joint PDF $f(H_s,U_{10})$ of wind speed and significant wave height. The joint PDF is calculated by the following formula:

$$f(H_s, U_{10}) = f_{H_s/U_{10}}(H_s/U_{10}) f_{U_{10}}(U_{10}) \tag{2}$$

where: $f_{U10}(U_{10})$ is the PDF of U_{10}, which is assumed to follow a lognormal distribution, as mentioned above and $f_{Hs/U10}(H_s/U_{10})$ is the conditional PDF of significant wave height H_s given the wind speed U_{10}. The distribution of the conditional PDF during a given storm is assumed to follow a Rayleigh distribution according to IEC 61400-3. Since, the PDF takes into account two variables its plot is depicted as a surface in 3D or in a 2D contour plot. The right graph of Figure 2 shows a contour plot of the joint PDF for the North site. Finally, it should be noted that a power-law wind profile was assumed for the distribution of the value of wind speed along the height *z* following IEC 61400-3.

Table 1 shows the results of the analysis for the characteristics of the North Site. In specific, the average values of the annual damage and the corresponding estimated fatigue life for both types of detail, as resulted from the Monte Carlo simulations of 100 years are listed. It was found that the size of the cross-section (i.e. diameter and thickness) has a significant effect on the annual damage for both details. As far as the diameter is concerned, the results show that the smaller diameter (5.50 m) is associated with higher annual damage. On the other hand, as the thickness increases the annual damage decreases. Both findings make an intuitive sense, since a smaller cross-section (e.g. smaller diameter and/or thickness) is expected to be more vulnerable to fatigue.

The annual damage is directly associated with the fatigue life. As mentioned in a previous subsection, the fatigue life is approximately equal to the reciprocal of the annual damage. From the results listed in Table 1, an inference is that the fatigue life (which is a more tangible magnitude in common sense than damage, since it is measured in years) depends highly on the size of the cross-section. In specific, regardless of the detail, as the size of the cross-section increases the expected fatigue life increases as well. Of course, this finding is intuitively expected, since a long fatigue life is associated with low annual damage.

Table 1: Results of Analysis for the North site

Thickness (mm)	DETAIL 40 MPa				DETAIL 71 MPa			
	Diameter = 5.50 m		Diameter = 6.00 m		Diameter = 5.50 m		Diameter = 6.00 m	
	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)
25	0.1941	5.15	0.1519	6.58	0.0243	41.22	0.0159	63.06
30	0.1045	9.57	0.0801	12.48	0.0114	88.05	0.0064	156.76
35	0.0610	16.40	0.0449	22.26	0.0056	179.69	0.0026	382.21
40	0.0379	26.38	0.0262	38.16	0.0029	346.95	0.0011	936.09
45	0.0241	41.46	0.0156	64.29	0.0015	659.42	0.0004	2473.80
50	0.0157	63.86	0.0094	106.24	0.0009	1182.20	0.0002	6403.04
55	0.0105	95.68	0.0057	174.55	0.0005	2021.50	4.839E-05	20671.37
60	0.0071	141.71	0.0035	285.91	0.0003	3227.00	1.337E-05	74830.91

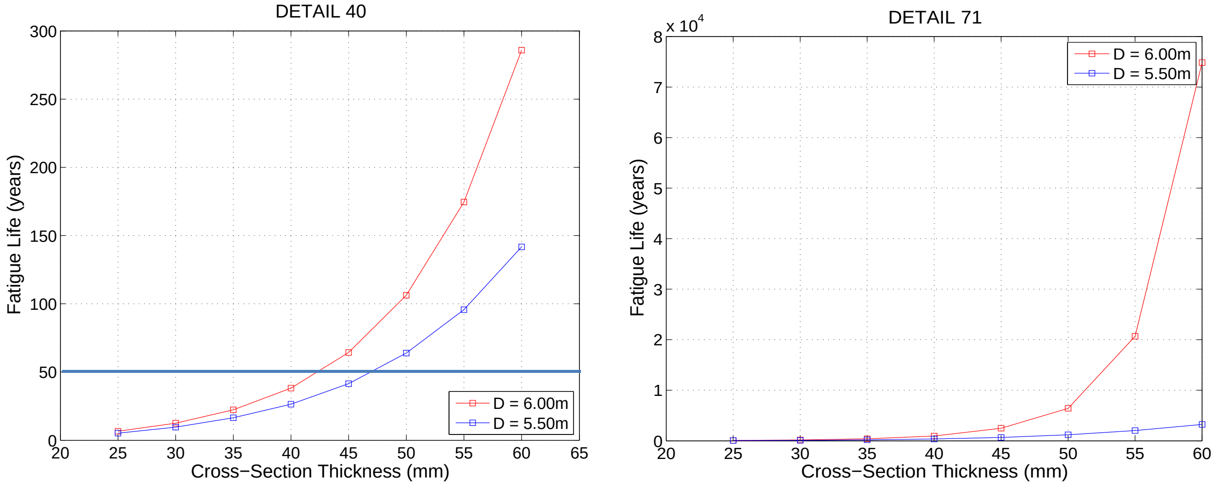

Figure 3: Fatigue life and geometry characteristics of cross-section for North site

It is noteworthy that the estimation of the fatigue life may be of special interest during the design phase of an offshore wind turbine. In other words, based on the expected fatigue life the designer is able to select an appropriate size for the pile's cross-section. This is because, it could be estimated whether a specific selection of cross-section's size and detail of connection will make the specific cross-section to last during the whole design life of the structure. For example, in the case of an offshore wind turbine the structure's life-time is usually considered to be equal to 50 years. Based on the values of Table 1, one could conclude that if a detail of 40 MPa is selected, the minimum thickness that is expected to last longer than the design life (with respect to fatigue) is 50 mm with a diameter of 5.50 m or 45 mm with a diameter of

6.00 m. For this reason a horizontal line is plotted in the fatigue life graphs of Figure 3 at the level of 50 years (the scale of the Y-axis of the graph of detail 71 MPa makes that line non-observable). The role of this line is to graphically show the combinations of diameter and thickness that result in fatigue lives longer than 50 years.

On the other hand, if a detail of 71 MPa for the welded connection is used the fatigue damage is expected to be significantly lower than in the case of 40 MPa. In specific, for a diameter of 5.50 m, only a thickness of 25 mm seems to result in a fatigue life shorter than the design life (fatigue life equals 41.22 years which is less than 50 years). Whereas, if a diameter of 6.00 m is used, no fatigue failure is expected during the life of the wind turbine, even for a thickness of 25 mm. However, the benefit of the absence of fatigue may be associated with a high price such as higher construction costs (larger cross-section, advanced welded connection).

5.2 Case 2: South Aegean Sea

The second site of this study was selected to be in the South Aegean. It was also assumed that this site is far enough from shore in order to use the same fetch (equal to 120 km) regardless of direction. This assumption is of course oversimplified but it has the advantage that it does not require the consideration of wind direction in the analysis. At this point, the authors would like to mention a legal limitation that may arise. As of today, Greece has not declared an Exclusive Economic Zone and its territorial waters are extended up to 6 nautical miles from the shore. Thus, any planned offshore wind farm would have to be placed inside the above 6-mile zone. For this reason, a site with such a large omnidirectional fetch may not yet be available for exploitation in the Aegean Sea. However, the authors performed an analysis in order to evaluate the effect of a duration-limited (rather than fetch-limited) sea state.

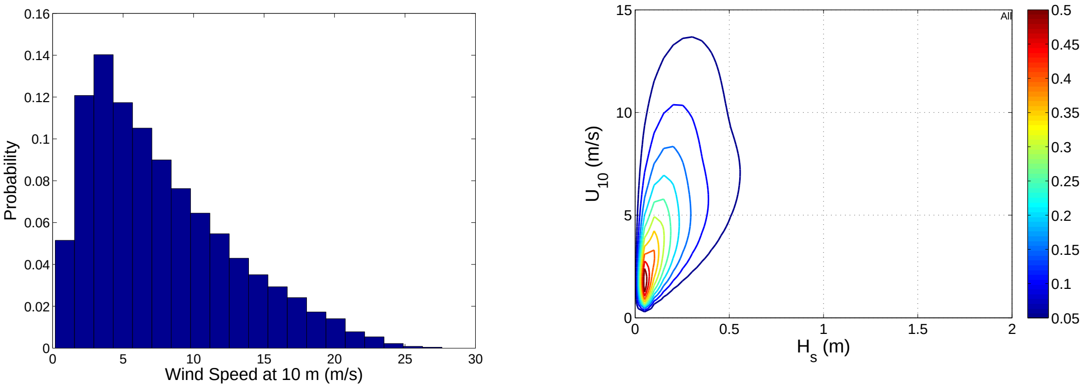

Figure 4: Distribution of non-zero 10 min mean wind speed at 10 m height for South site (left graph). Contour plot of the joint PDF $f(H_s,U_{10})$ (right graph)

Figure 4 (left graph) shows the distribution of the wind speed at 10 m at the South site. A statistical analysis showed that the mean value of the wind speed is equal to 7.74 m/s and the standard deviation is equal to 5.10 m/s. Thus, a first inference is that South site is characterized by higher wind speeds than the North site. Finally, it was found that a Weibull (and not a lognormal) distribution with parameters λ = 8.65 and k = 1.58 provides the best fit. Figure 4 also shows the contour plot of the joint PDF $f(H_s,U_{10})$ for the South site (right graph). Now, all contours have an "oval" shape since the same fetch is assumed for all directions.

Table 2: Results of Analysis for the South site

Thickness (mm)	DETAIL 40 MPa				DETAIL 71 MPa			
	Diameter = 5.50 m		Diameter = 6.00 m		Diameter = 5.50 m		Diameter = 6.00 m	
	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)	Annual Damage	Fatigue Life (yrs)
25	1.0025	1.00	0.5791	1.73	0.1391	7.19	0.0687	14.55
30	0.5574	1.79	0.3130	3.20	0.0680	14.71	0.0304	32.91
35	0.3335	3.00	0.1812	5.52	0.0350	28.53	0.0139	72.02
40	0.2102	4.76	0.1087	9.20	0.0186	53.68	0.0064	157.20
45	0.1372	7.29	0.0676	14.80	0.0101	99.10	0.0031	326.10
50	0.0918	10.89	0.0429	23.29	0.0056	180.18	0.0015	674.38
55	0.0629	15.90	0.0276	36.20	0.0031	317.58	0.0007	1394.30
60	0.0438	22.83	0.0179	55.77	0.0018	553.93	0.0003	3048.30

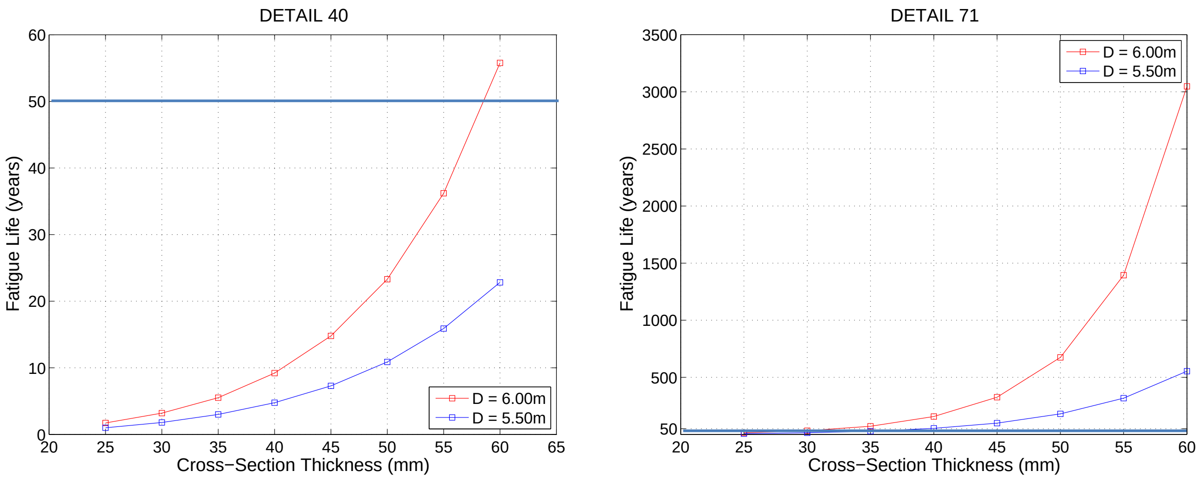

Figure 5: Fatigue life and geometry characteristics of cross-section for South site

The Monte Carlo analysis gave the results shown in Table 2. The results, as expected, follow the same trends as in the case of the North site. However, due to the higher wind and wave conditions of the site, very large values of annual damage and low values of fatigue life were calculated. It is noteworthy that for a detail of 40 MPa, a diameter of 5.50 m is too small since it is always associated with fatigue lives shorter than the design life. Moreover, even if a diameter of 6.00 m is used, then the thickness should be at least 60 mm in order the fatigue life to be larger (only about 6 years) than 50 years. For this reason only the combination associated with 6.00 m of diameter and 60 mm of thickness is above the reference line of 50 years in the left graph of Figure 5.

If a detail of 71 MPa is selected, then longer values of fatigue life are expected. However, it should be mentioned that even with the better detail, only if the thickness of the cross-section is larger than 35 mm with a diameter of 5.50 m or 30 mm with a diameter of 6.00 m, the estimated fatigue life is greater than the design life of the wind turbine. Finally, if a value of thickness equal to 60 mm with a diameter of 5.50 m or larger than 45 mm with a diameter of 6.00 m is used, then the estimated fatigue is greater than 500 years (10 times the design life) and no fatigue failure is expected in practice.

6 CONCLUSIONS

In this paper, a probabilistic fatigue life assessment for a standard offshore wind turbine with a monopile design was presented. Two potential sites of construction in the Aegean Sea of Greece with different wind and wave characteristics were examined. A fully coupled dynamic analysis for the calculation of loadings due to wind and wave was performed using the freely available FAST software. The assessment of fatigue damage (and corresponding fatigue life) was made considering two different details of welded connections according to EC3 for the cross-section at mudline of the structure.

The results follow the obvious trends: Turbines at windier sites with longer fetch distances are obviously more vulnerable to fatigue. Lower quality fillet welds similarly attract higher fatigue damage compared to more expensive butt welds. The size of the cross-section is a crucial parameter for the design, since small diameter and/or thickness may result in a very quick fatigue failure, especially in the case of fillet welds.

The inferences from the above discussion may be useful, especially during the design of the foundation pile. Fillet welds might not be appropriate in a construction site characterized by windy conditions, however they might be a potential cost-reduction technique for sites with less intensive wind loads, since they are much cheaper to execute than butt welds and with an appropriate cross-section’s size may last more than the design life.

Finally, as an overall conclusion of this work is that the accuracy offered by a detailed probabilistic approach can help in properly quantifying the actual performance of the structural components and thus result to a better compromise between safety and economy. Incorporating further sources of uncertainty and operational states of the wind turbine (e.g., starting and stopping) will only improve the accuracy in such predictions and help offer a cost-effective custom-made solution for a site of interest.

ACKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund - ESF) and Hellenic national funds through the Operational Program "Competitiveness and Entrepreneurship" of the National Strategic Reference Framework (NSRF 2007-2013) - Research Funding Program: Bilateral R&D Cooperation between Greece and China 2012-2014.

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