An optimised approach in geotechnical design using locally prescribed storm event

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ABSTRACT

This paper describes aspects of the foundation design, relating to storm event considerations, developed for an offshore wind farm in Taiwan, supported on monopile foundation in water depths of 15 m to 30 m. The foundation design was first initiated assuming cyclic degradation applicable to Ultimate Limit State (ULS) case, and considering the uncertainty present, was further developed to allow for a site-specific storm event using site measurement to be implemented, representative of local conditions. The evaluation of the prescribed storm event informed the assessment of the equivalent number of cycles of maximum loading, as a mean of supplementing the cyclic degradation of the soil expected in design. The technical review involved a detailed process with the certifier that contributed to the development of acceptable design and mitigated risks relating to cyclic degradation and foundation performance.

Keywords: Taiwan storm event; BSH storm event; S-N curves for soils; Offshore wind farm, equivalent number of load cycles, Markov matrix

1 INTRODUCTION

This paper concerns the foundation design and performance of an offshore wind farm in Taiwan, thus bearing significant uncertainties due to the absence of extensive databases similar to those in Europe. The wind turbines are supported by monopile foundations in water depths of 15 m to 30 m.

The site investigation campaign together with the laboratory testing facilitated the development of cyclic concept in the geotechnical design. Some aspect of the foundation design such as the foundation performance under cyclic loading were not covered by the design code and instead reference was made to the code published by the German Federal Maritime and Hydrographic Agency (BSH, 2015).

In order to assess the load-time histories to be employed as part of ULS, load effects with at least a 50-year return period are considered. The data analyses are based on a nearly 20 year long time series of wave data collected from the Hsinchu Buoy. The purpose of the study is to compare measured storm events with the standard 35-hour duration storm event as given in (BSH, 2015) and to prescribe a site specific ULS storm event and its impact on the effect of cyclic loading on foundation design.

2 DATA VALIDATION

The wind and wave data used for the present study, have been collected at the Hsinchu Buoy since 1997 and has a duration of nearly 20ements at the Hsinchu Buoy are taken at a height of 2.3 m (with respect to the Taiwanese Vertical Datum, TWVD), while the wind data at the Metmast is taken at 90 m TWVD. Using a standard conversion fit, the Hsinchu Buoy wind speeds are converted to 90 m TWVD. The time series plot in Fig. 1 shows the wind speeds during the typhoon Nepartak measured at the Hsinchu Buoy (red curve), the wind speeds measured at the Metmast at 90 m elevation (black curve) and the Hsinchu Buoy wind speeds converted to 90 m elevation (green curve).

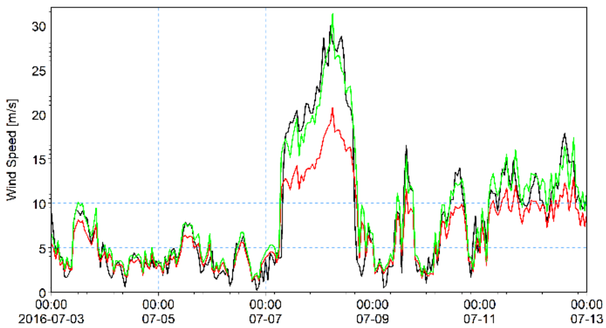

Fig. 1. Wind speed measured during the typhoon Nepartak (Curves described in text).

As can be seen from the comparative plot in Fig. 1, there is a very good correlation between the Hsinchu buoy measurements scaled to 90 m elevation and the corresponding Metmast measurements. This applies both for the shape of the storm as well as for the peak values.

3 STORM EVENTS

3.1 Storm duration analysis procedure

The procedure adopted for estimating the duration of a given storm is as follows:

- Definition of a factor representing the ratio between the significant wave height at the start and the end of a storm, compared to the peak value during the most intense period of the storm. For the standard BSH 35-hour storm the factor is $\alpha = 0.5$.
- Only events with H_s >3m were considered.
- A minimum separation period of 48 hours between consecutive storms is applied.

3.2 Storm duration

An example showing the most severe storm event (i.e. largest peak significant wave height) measured at the Hsinchu Buoy is given in Fig. 2. The envelope corresponding to a standard 35 hour BSH storm (BSH, 2015) has been overlaid at the time series plots.

The example shown in Fig. 2 indicates that the BSH storm definition severely exceeds the actual storm duration. This is also the case for most of the measured severe storms. For many of the smaller peak values, the BSH storm definition gives a better fit.

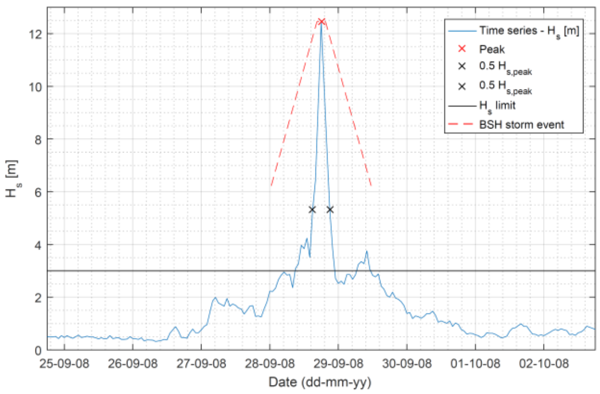

Fig. 2. Storm event measured during the typhoon Jangmi in September 2008 and corresponding BSH 35-hour storm event (BSH, 2015).

4 PROPOSED SITE-SPECIFIC STORM EVENTS

4.1 Significant wave height

An analysis of the storm development (storm growth and storm decay) is performed for the largest storms measured at the Hsinchu Buoy, using the methodology described below:

- The significant wave height (H_s) time series for the 24 hours before and after peak H_s is extracted (cf. section 3.1).
- For each storm, the normalized significant wave height is calculated as

$$a(t_i)=H_s(t_i)/H_{s,peak} \qquad (1)$$

where $-17.5 \le t_i \le 17.5$ denotes the time in hours relative to $t(H_{s,peak})$.

- For each time step, t_i, the mean and standard deviation of $a(t_i)$ is calculated.

The normalized storm events versus the proposed envelope for storm development for the 4 and 10 largest storms measured is presented in Fig. 3 and Fig. 4. The BSH storm event definition (BSH, 2015) is included for comparison. Individual storms are plotted with a marker at each data point to show the coverage of data of the Hsinchu Buoy time series. It is observed that the mean growth and decay period increases with reduced $H_{s,peak}$. The 4 storms with $H_{s,peak}$ > 8m have a very rapid growth and decay compared to the standard BSH storm event.

Based on the above analysis, a site-specific storm event is defined conservatively as the mean + 1std storm development of the 10 largest storms measured.

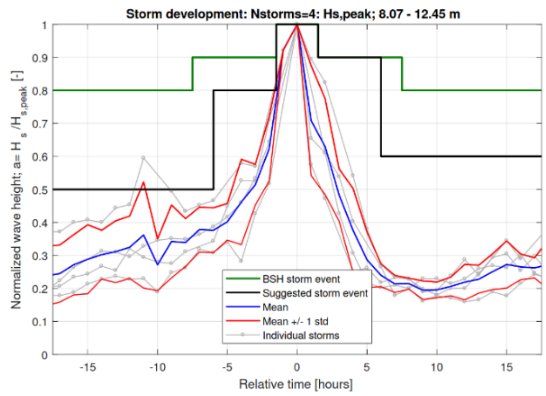

Fig. 3. Site specific storm development based on the 4 largest storms measured at the Hsinchu Buoy

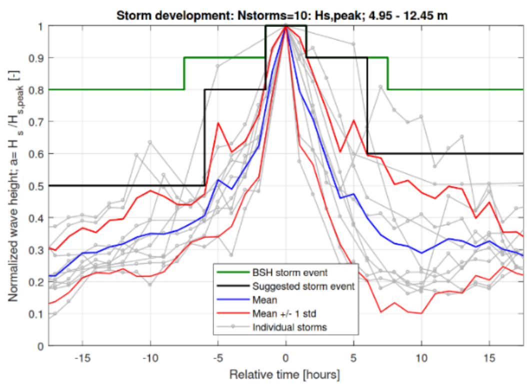

Fig. 4. Site specific storm development based on the 10 largest storms measured at the Hsinchu Buoy.

4.2 Wind speed

In Fig. 5 and Fig. 6 is shown the proposed storm event versus the measured storm development for the 4 and 10 largest storms, respectively.

It is observed that the mean growth period decreases and the mean decay period increases with reduced

$H_{s,peak}$. The 4 storms with $H_{s,peak}$ > 8m have a less rapid growth and a very rapid decay, when compared to the standard BSH storm event.

Based on the above findings, a site-specific storm event is defined conservatively as the mean + 1std storm development of the 10 largest storms (similar to the definition adopted for the wave height). The site-specific storm event is divided into steps of equal duration as the ones described in Section 4.1.

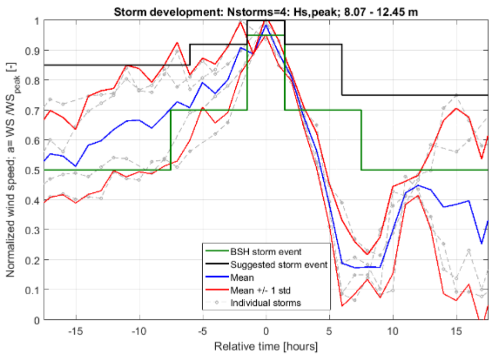

Fig. 5. Site specific storm development based on the 4 largest storms measured at the Hsinchu Buoy

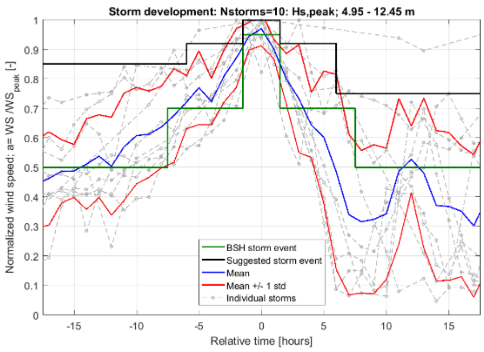

Fig. 6. Site specific storm development based on the 10 largest storms measured at the Hsinchu Buoy

5 MONOPILE RESPONSE DURING STORM

5.1 Assembly of storm event

Times series of shear and moment obtained through the project for the given site conditions described above, are assembled for the analysis to form each of the steps of the design storm profile, see Fig. 7. The locally prescribed storm is constructed from different plateaus, each made up of smaller series of 10-minute coupled hydrodynamic/structural analyses with different characteristics, i.e. wind directions, wind speed, yaw error, turbulence model and sea-state. The assembly is done through a computational procedure where the 10-minute time series are randomly picked from the pool of samples and concatenated It should be noted that the ULS is included in one of the 10 mins time histories simulated in the peak of the storm.

For conservatism, the applied times series assume collinear loading of wind and waves. The time series resembles the pulsating load levels the foundation is subjected to, whereby the peak plateau evident corresponds to the 50-year design wave that forms the basis for ULS design loads.

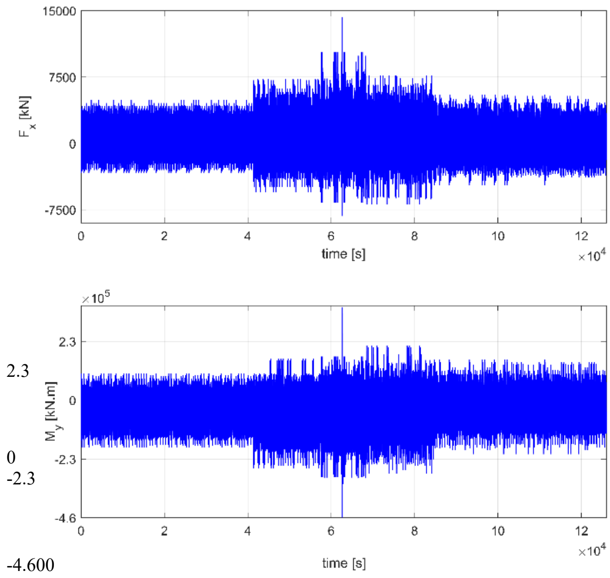

Fig. 7. Assembled storm, shear (top figure) and moment (bottom figure) time series.

5.2 Pile head displacements

The response of the pile is calculated under the loading conditions displayed in Fig. 7. This results in two displacement time series developed at pile head, representative of loading in both directions, plotted for each load increment of the storm, see in Fig. 8.

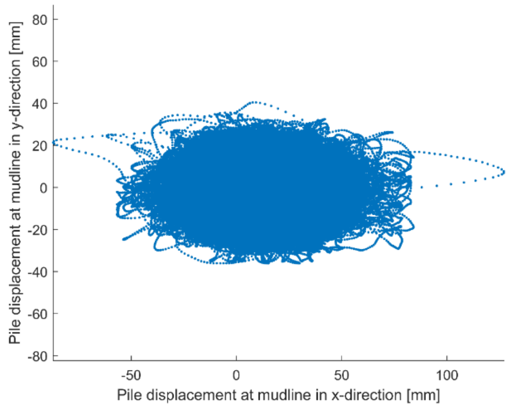

Fig. 8. Displacement at pile head during design storm event (along x- and y-axes independently)

It is evident that the x component influenced by the loading direction is governing thus resulting in a positive displacement at pile head.

6 NUMBER OF EQUIVALENT LOAD CYCLES

6.1 Methodology

The calculations of equivalent number of load cycles aim to validate the p-y curves assumptions for accounting cyclic effects on soil-pile interaction, valid up to 100 cycles.

The main assumption of the assessment, i.e. the degradation law, comes from the methodology highlighted in Lin and Liao (1999) for cyclic lateral loads on piles in sand. The logarithmic equation provides the cyclic lateral displacement at seabed as a function of its respective static displacement x_{static} and the number of cycles N.

The degradation factor t is derived based on the formula introduced by Long and Vanneste (1994), and the guidelines by Lin and Liao (1999). The parameter t is conservatively estimated between 0.22 and 0.26 as lower and upper bounds.

6.2 Rainflow counting

Cyclic pile tests and laboratory soil element testing are routinely conducted to assess the effect of cyclic loading on design using fixed frequency with regular amplitude cycles. The design storm is assembled of a succession of a non-uniformly distributed irregular amplitude load cycles. In order to ascertain the effect of a regular amplitude load cycle, the design time history is transformed such that idealised series of uniform cycles with average load and cyclic load amplitude, accounting for peaks and troughs are discretised representative of each of the length of the steps The idealised uniform load cycles are arranged as a Markov matrix and are plotted in Fig. 9. The figure suggests a total of nearly 70,000 load cycles.

6.3 Validation of p-y curves

Using the equivalent strain method, (Stewart, 1986), the corresponding pile head displacements are related through the degradation law.

The procedure calculates the number of cycles needed to reach the same displacement as the previous step with the static displacement of the current step. The current step considers then, the number of cycles of the current step given by the rainflow count in addition to the previous equivalent number of cycles calculated. The displacement is therefore aggregated, see Fig. 10. It is carried out over the entire storm duration and starts with the smallest deflection range, subsequently shifting to the second smallest, eventually up to the deflection caused by the 50-year ULS design load, determining the number of cycles equivalent to the deformation of the entire time history. As cyclic p-y curves are valid up to 100 cycles in ULS, this forms the verification threshold. Results of the analysis show a number of equivalent cycles between 3 and 5.

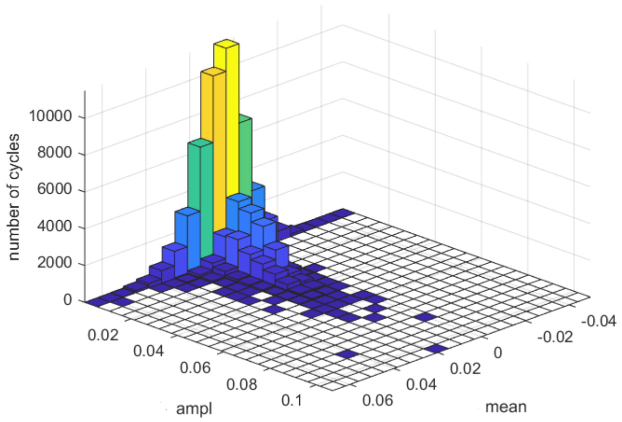

Fig. 9. Graphical view of deflection Markov matrix. (matrix dimension 20 bins x 20 bins)

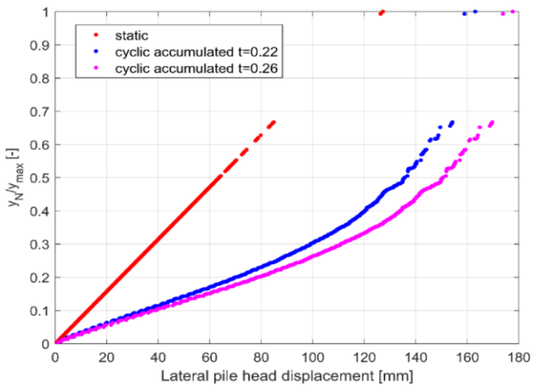

Fig. 10. Accumulated cyclic degradation during storm event calculated with and without degradation.

7 CONCLUSION.

This paper recommends the development of the locally prescribed storm event based on site-specific data. Subsequently, the storm is implemented in foundation design as a mean of verifying the assumptions behind the use of cyclic load effects. The Lin and Liao (1999) method is used to approximate the cyclic degradation due to the loading conditions on site and the equivalent number of design load cycles for the whole storm is estimated. The results are in agreement with the current understanding developed based on the extensive database available for the North Sea. The final result is similar to values calculated for the North Sea.

8 REFERENCES

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