REVISITING GLOBAL RESPONSE OF FPSOS IN SHALLOW WATER AND THE RISER ANALYSIS REQUIREMENTS

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ABSTRACT

Analysis and design of riser systems for permanently moored FPSOs/FSOs in shallow water are known to be extremely challenging. The complex nature of shallow water hydrodynamics and dynamic responses of the FPSO in extreme environmental conditions, limitations caused by water depth, and the close proximity of risers to each other and other structures, define significant technical and practical challenges for the riser designer. These challenges are typically magnified by conservative estimates of the global response of the FPSO system.

The new riser design codes tend to be vague about global riser analysis requirements and do not clearly define the global mooring analysis outputs, i.e. vessel offset and correlation between low-frequency offset and maximum wave height, to be used in riser detailed analysis. The codes commonly refer to the fully coupled mooring-riser system analysis for more realistic representation of the behavior of the system but do not provide guidance on the application of various offsets, associated directions, and environmental conditions. However, due to the large analysis matrix and level of numerical modeling required for detailed riser analysis, the fully coupled mooring-riser system analysis is not typically used by riser designers in the actual project phase. It is common to perform the riser analysis by assuming the vessel is at an extreme offset and performing dynamic analysis about that location with the maximum wave by using a time history of regular waves, or segments of random wave elevation time histories that contain the maximum wave. While this approach may not cause much difficulty for deepwater riser systems, it has a profound effect on the performance of riser systems in shallow water, leading to challenges in both the design and costs associated with such a system as it exaggerates the dynamic response of the floater, and the loading on the riser system.

In this paper, model test data and numerical time-domain simulations have been utilized to revisit the response of typical shallow-water FPSOs in extreme conditions. The main purpose here is to discuss the natural response of the system and highlight the correlation between the low-frequency and wave-frequency responses.

Keywords: FPSO Response, Shallow Water, Riser System Design, Offset Requirement

INTRODUCTION

In most offshore projects, the mooring and riser designs are typically performed by separate teams and the main interface between these groups is the definition of the global response of the floating system in different environmental conditions. There is, however, a disconnect between the way the vessel offsets are developed and reported by the mooring designer and how they are then applied in the riser system design. As a solution, the new riser design codes and standards rely on advancements in numerical calculations and commonly refer to the fully coupled mooring-riser system analysis for more realistic representation of the response of the system. However, due to the large analysis matrix utilized in the riser system design and the level of details needed in numerical modeling of risers, the fully coupled mooring-riser system analysis is not typically used in detailed analysis and design of the riser system in the actual project phase. Typically a simplified uncoupled approach is utilized where extreme quasi-static offsets defined by the mooring analyst are combined with a simplified representation of extreme wave-frequency responses.

In general, the total global response of the mooring system to environmental loadings can be divided into three main components: mean, low-frequency (LF), and wave-frequency (WF). The mean component is the static response of the system to the mean environmental loadings, LF response refers to the response of the system to the slow drift forces and occurs at the system natural period, and the WF component refers to the dynamic response of the system to the wave action. As an example, the components of the turret offset for a shallow water system are presented in Figure 1. In frequency domain calculation, the contribution of each term is calculated separately while in the time domain approach the total response is typically calculated directly. The term quasi-static offset, called offset for simplicity, refers to the combination of mean and LF components of the total horizontal motion at the riser top connection, e.g. turret center. The extreme statistics of the offset can be easily obtained from the summation of the mean offset and the extreme LF offset in frequency domain approach. In time domain approach, the quasi-static offset timeseries can be obtained from low-pass filtering of the total horizontal motion signal and its extreme statistics can be estimated by performing extreme analysis on the sample data from multiple realizations.

For uncoupled riser analysis, the vessel is placed at a pre-defined quasi-static offset and the dynamic response of the riser is captured by using regular waves or segments from a random wave time history and allowing the vessel to only respond to the WF loads. The new design codes and industry guidelines tend to be vague about the vessel offset requirements for uncoupled riser analysis which adds to the confusion and results in conservative and in some cases unrealistic assumptions about the global response of the system. In some cases, the general recommendations about offset requirements for riser analysis purposes in the earlier revisions of the design codes have been removed from the latest revisions, e.g. API RP 17-B fourth and fifth editions. One main reason for these modifications can be related to the industry's general tendency to remove prescriptive requirements from the new codes and standards to give the users more flexibility to define appropriate criteria. This approach has provided room for the development of project specific requirements and criteria which in general is positive. On the other hand, the offshore industry has been mainly focused on deepwater developments in the past few years and the common practices have been updated to mainly consider the challenges associated with the deepwater related concerns. In some cases, these new common practices and requirements do not distinguish between deepwater and shallow water applications and miss the fact that the response of the deep water and shallow water systems could be significantly different.

As indicated in previous studies (Duggal et al. 2004), the complex nature of shallow water hydrodynamics in extreme environmental condition, non-linearity of mooring system response, limitations caused by water depth, and the close proximity of risers to each other and other structures define significant technical and practical challenges for the riser designer. These challenges are typically magnified by conservative estimates of the global response of the system resulting in significant technical challenges and cost impact on the riser system design. Therefore, it is prudent to evaluate the global response requirements and the common practices used in riser system design.

FPSOs in shallow water are characterized by stiff mooring systems and very low system damping, i.e. typically less than 10% of the critical damping, leading to high dynamic response primarily around the natural surge period, i.e. typically less than 150 seconds. This results in small mean offset to the environment load, coupled with large LF dynamic response which could be significantly larger than the mean offset in some cases. This can be seen in the example shown in Figure 1 where the main contributor to the total horizontal offset is the LF component and both mean and WF contributions are significantly smaller. In contrast deepwater systems are quite heavily damped, i.e. around 30-60% of critical and thus the low frequency dynamic offsets are less pronounced.

In recent years, there have been efforts to better incorporate the global response of the system into riser system design with the goal of eliminating the unnecessary conservative assumptions. For instance, an integrated mooring-riser system design approach is being used (Martens et al. 2011) more frequently in which the estimate of vessel offset for the specified seastates are directly used by the riser designer instead of using a pre-defined maximum offset for all environmental combinations.

Following these efforts, in this paper the correlation between the vessel LF offset and the maximum wave height is studied. The focus of this study is on the shallow water systems as the correlation between LF and WF responses tends to play a more important role in shallow water systems as compared to the deepwater systems. The main motive here is to shed light on some of the known basics and revisit the assumptions made in riser analysis and design with respect to the mooring system global response characteristics.

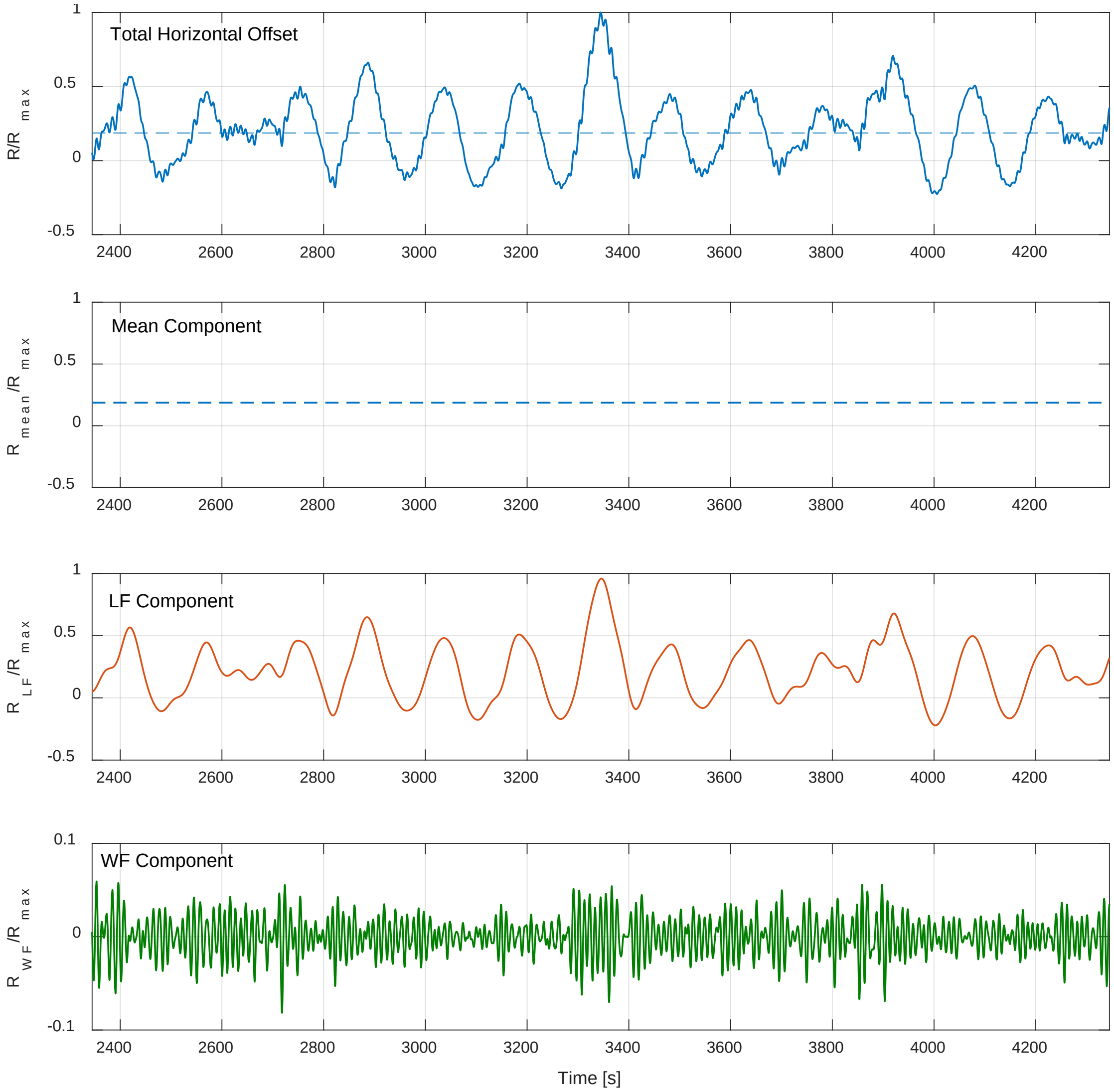

Figure 1 Example of turret offset of a shallow water system and the contributing components

UNCOUPLED RISER ANALYSIS REQUIREMENTS

The term uncoupled analysis has different applications in the field of ocean engineering so it is worth defining the term for riser analysis application. The uncoupled riser analysis is typically referred to the type of analysis in which the riser detailed analysis and design is done separately from the global mooring system response analysis. For this purpose, the vessel is placed at a representative quasi-static offset and the vessel WF responses and loads on the riser are captured by vessel motion RAOs and applied waves. These waves are typically applied as a short time history of regular waves with height equal to the maximum wave height or short segments of random wave elevations that include the maximum wave. The vessel offset itself may have been calculated from a coupled global mooring response analysis in which the effect of risers on the global system response, i.e. stiffness and damping effects, is captured. The main question to investigate here is how the representative quasi-static offset and the parameters of applied wave condition are defined and how the correlation between LF and WF responses are captured in the uncoupled riser analysis.

The mooring design codes, e.g. API RP 2SK, DNVGL-OS-E01, and ISO 19901-7, consistently define the total design offset, i.e. Most Probable Maximum (MPM) offset in a 3hr storm, using the following expression:

Design Offset = max [Mean Offset + MPM (LF Offset) + significant (WF Offset),
Mean Offset + significant (LF Offset) + MPM (WF Offset)]

The expression is recommended for frequency domain calculation where the LF and WF responses are calculated separately. In time domain approach, the total offset is calculated directly and the quasi-static offset is obtained by filtering the WF contribution. Multiple realizations are required to estimate the statistics of the extreme quasi-static offset in time domain approach.

The mooring codes, however, do not provide a clear guideline on the way the global analysis information should be used for the uncoupled riser analysis purposes. The riser design codes, e.g. API RP 17-B and DNV-OS-F201, are not very specific about how the global analysis inputs need to be considered for riser analysis and design either. Consequently, it is common for riser analysis and design to assume that the extreme LF offset happens at the time of the extreme wave height. Specifically, for riser analysis purposes the vessel is located at the extreme LF offset, i.e. MPM or Expected maximum LF offset in a 3-hour storm, and WF extreme responses are captured by applying either a regular wave with the MPM wave height and associated period or a short window of irregular wave timeseries containing the MPM wave height. The underlying assumption of this approach is that WF and LF responses are fully correlated and their peaks coincide. While this approach may not cause much difficulty for deepwater systems, it could have significant impact on the design of the shallow water riser systems. This approach is assumed to be conservative and if the riser system is not affected by the assumption is an efficient approach when it comes to riser analysis and design. However, for shallow water systems in relatively harsh environments, this conservative assumption can have a very large impact on the riser analysis and design, impacting the riser structure design, the riser configuration, and even the design of the FPSO and its mooring system.

This discussion can be extended to the ways the phasing between the vessel WF motions, e.g. turret vertical motion, and the wave loads on the riser are captured in uncoupled riser analysis. Furthermore, defining the parameters of the applied regular wave is debatable and attention has to be given to the response of the system and governing factors while defining the parameters of the applied regular wave. This paper briefly discusses some of these topics but the main focus remains on considerations made in combining LF response and the wave height.

CASE STUDY

As a case study the response of an external turret-moored system in extreme condition is evaluated. The studied case is an FSO with a typical external turret designed for a water depth of 60 meters in relatively benign conditions with a 100-year return period Hs of about 7.0 m. The mooring system consists of 9 catenary anchor legs arranged in 3 groups of 3 identical anchor legs. Each anchor leg is made of all chain components. The vessel is an Aframax size converted tanker with a relatively small topside area meaning that the vessel quasi-static response is dominated by wave loading. Schematic views of the mooring and riser system of the studied case are shown in Figure 2. As shown in this figure, the risers have a lazy S configuration supported by a midwater arch.

In this study, the scaled model test data for the most critical loading condition and the most critical environmental combination is used. The environmental condition represents a design 100-year return period condition. The data from 5 independent model test realizations have been utilized. Moreover, the results of time domain calculations of this FSO system have been used to obtain better estimates of the statistics. The surge natural period for this condition is about 130 seconds.

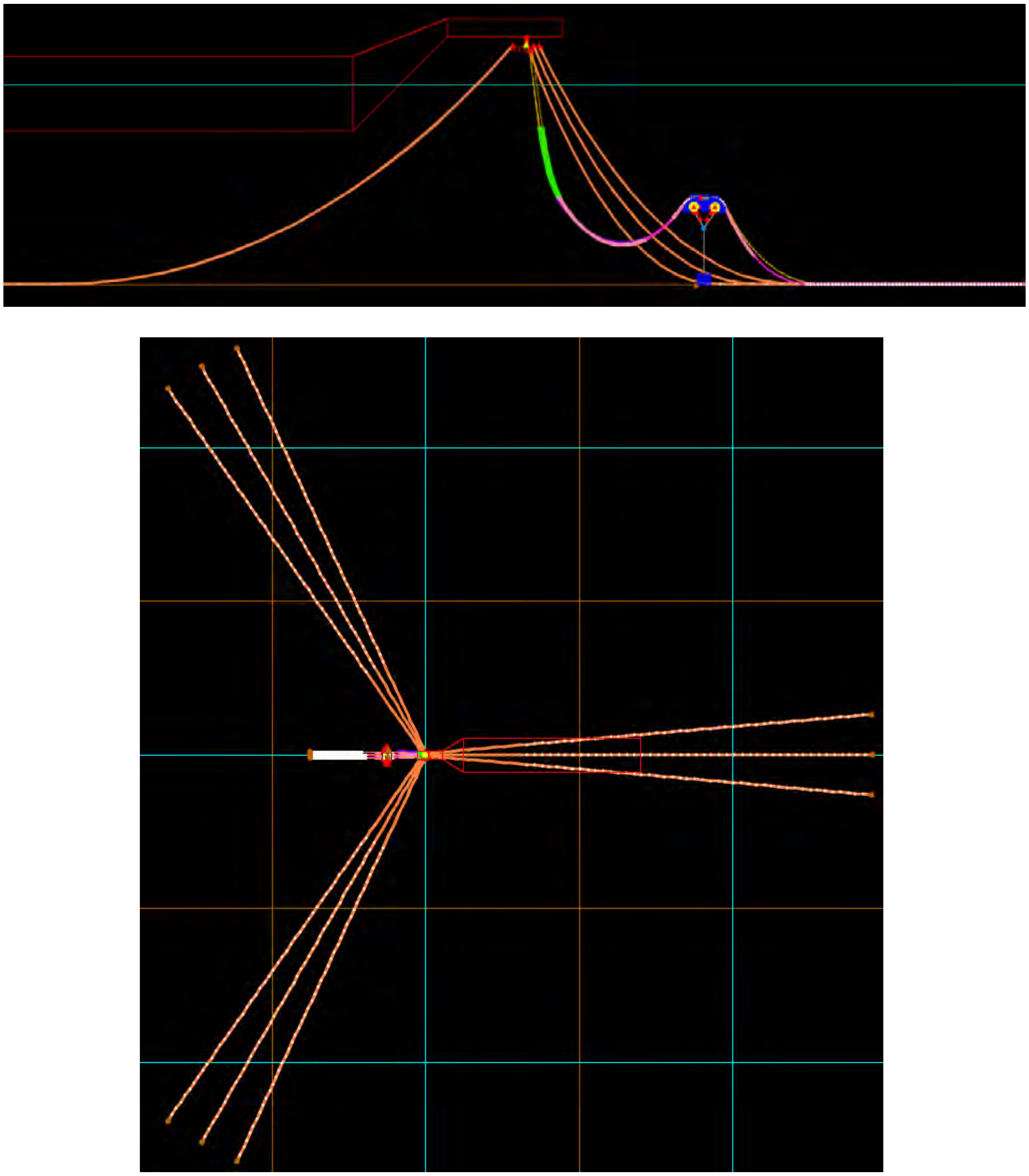

Figure 2 Schematic views of the studied mooring system

DISCUSSION ON GLOBAL RESPONSE OF THE MOORING SYSTEM

The vessel quasi-static offset is a combination of the static mean offset and the dynamic LF offset. Physically, large LF offsets for lightly damped systems can be seen to occur after a large group of waves within the realization interact with the vessel. Generally speaking, the vessel LF offset is a function of the intensity of the wave group and the vessel initial condition. The maximum individual wave height, however, may or may not be part of the wave group with the highest intensity. This is illustrated in Figure 3 which shows the measured model test timeseries of wave elevation and turret offset for the Case Study. In this figure, the results of 5 different realizations are presented and the location of maximum observed wave height and maximum observed vessel offset in the 3-hour test are highlighted. The offset estimates in Figure 3 are transposed into the wave direction and therefore a positive offset indicates a downstream turret offset and a negative offset refers to an upstream turret offset. For the ease of comparison, the timeseries in this figure are normalized by the average of the observed maxima of the five seeds, i.e. average maximum downstream offset and average maximum wave height. Due to the nonlinearity of waves, the crests and troughs are not symmetrical around the zero mean position but the wave heights seem to be almost linear and they follow the Rayleigh distribution relatively closely.

As shown In Figure 3, the absolute maximum observed offset and maximum observed wave height could be far apart indicating that the wave group with the highest intensity may not contain the largest wave. The five 3-hour simulations show that time from a few hundred to several thousand seconds can occur between the two maxima. This indicates that the maximum offset and maximum individual wave height are uncorrelated. However, the maximum offset happens after a large wave group that contains a relatively large individual wave. To investigate the correlation between the extreme offset and the extreme wave height, a few examples of extreme incidents from the 5 seeds are selected and the timeseries for a shorter period are presented in Figure 4.

The first example (Figure 4 (a)) is a typical response of the mooring system to a large wave group. As shown in this figure, the extreme offset happens with a time lag after the end of the large wave group. The large wave group in this case contains a relatively large individual wave height, i.e. smaller than the maximum observed wave height in the timeseries. The important note here is that even though an extreme wave height has resulted in the maximum offset, the extreme wave height and the maximum offset do not coincide. Like any spring and mass system, the time lag between the maximum loading and maximum response depends on the system characteristics, i.e. mass properties, damping, and initial condition, etc.

The first part of the second example (time <6250sec of Figure 4 (b), is similar to what was seen in the first example where a large wave group results in an extreme offset. It is however seen in the second example (time > 6250sec) that the wave group dies out and wave elevation remains low for quite some time. This allows the restored force in the mooring system to cause a significant upstream offset. On the cycle after the maximum upstream offset, the system experiences another large wave group that results in the second large offset. As can be seen here the wave group ends with a large individual wave and consequently a large offset that is slightly less than the maximum offset coincides with a large individual wave height that is smaller than the maximum observed wave height. This example highlights the importance of considering the randomness of wave elevation and vessel response in analysis and design process.

The third example (Figure 4 (c)) shows the maximum observed wave height that was not accompanied with a large wave group. As shown in this figure, the maximum observed wave height did not result in a significant offset.

These examples highlight that extreme wave height and extreme vessel offset have a cause and effect relationship but their peaks do not typically coincide and therefore assuming that MPM wave height occurs with the MPM offset for riser design is an extremely conservative approach. This is why the mooring design codes combine extreme quasi-static offsets with significant WF responses and vice-versa.

As a side note, this discussion is extended to the correlation between wave height and turret vertical motion. As indicated earlier in this paper, riser analysis is typically done using regular wave analysis with MPM wave height and associated wave period or irregular wave analysis of a short time span containing the MPM wave height. Similar to Figure 3, the timeseries of normalized wave elevation and turret vertical motion from the five 3hr seeds are presented in Figure 5. The turret Z motion is normalized with the average of maximum positive Z motion of the five seeds. The turret Z has a linear behavior with peaks following Rayleigh distribution. The turret vertical motion is a result of vessel pitch motion and vessel heave motion while the pitch motion is the dominant contributor. It is worth mentioning that the surface elevation is measured at turret original offset so a few seconds of time shift is expected between surface elevation and turret vertical motion. The location of maximum observed wave height and maximum and minimum observed turret vertical motions is indicated in Figure 5. As shown here, even though a strong correlation between vertical motion and wave elevation exists, the maximum wave height may not necessarily result in the maximum turret vertical motion. As expected the wave period associated with the extreme wave height plays an important role on the vessel WF response.

Similar to Figure 4, a few incidents of extreme wave height and extreme turret vertical motion are highlighted in Figure 6. The main remark here is that in case the riser design is sensitive to turret vertical motion, which is typically the case in shallow water designs, attention has to be given to the wave period associated with the maximum wave height. This is more relevant when regular wave analysis is being used for riser analysis purposes.

STATISTICAL ANALYSIS OF EXTREME OFFSET AND EXTREME WAVE HEIGHT

To perform a statistical analysis on the extreme offset and extreme wave height, the results of numerical time domain simulations have been used. The numerical model is based on the same system that was model tested and its performance has been verified using the model test data. The same load case and vessel loading condition as used in the model test campaign has been used in this example. For this purpose, the results from 50 independent 3-hour simulations have been utilized. To increase the sample size the peaks-over-threshold method has been used and threshold is defined as 90% of average observed maxima from 50 realizations.

In Figure 7, the correlation between extreme offsets and associated wave heights, and extreme wave height and associated offset is presented. The data points in this figure are normalized with the appropriate average observed maxima from 50 realizations. Figure 7 (a) shows the wave height at the time of the maximum observed offset. As can be seen in Figure 7 (a), the maximum observed offset from the 50 realization is equal to 1.15 times of the expected maxima. These maximum observed offsets occur with an individual wave height that is less than 60% of the expected maximum wave height. Similarly in Figure 7 (b) the offset at the time of the maximum observed wave heights are reported. As shown in this figure, the maximum observed wave height in 50 seeds is more than 1.15 time the expected wave height and this wave height is associated with an offset that is less than 65% of the expected maximum offset. It is also important to note that the extreme offset and extreme wave height do not necessarily happen at the same time and as can be seen in Figure 7 (a) and Figure 7 (b), there is no clear correlation between the extreme observations of the two random variables.

In Table 1, the statistics associated with the extreme events are presented. In this table, Hs and Rs refer to the significant wave height and significant vessel offset, respectively. As shown in this table, the average wave height associated with maximum offset is about 65% of Hs and 36% of expected maximum wave height. Similarly, the average offset associated with maximum wave height is about 62% of significant quasi-static offset and 48% of expected maximum offset. To compare, the mooring design codes combine the MPM quasi-static offset with significant WF response, i.e. E (H) / Hs = 1.0, and combine the MPM WF response with significant quasi-static offset, i.e. E (R) / Rs = 1.0, which is more conservative than the results obtained here. Therefore, the recommendation made by mooring design codes to combine the MPM, or expected maximum, quasi-static offset with maximum WF response and vice-versa is better suited for riser analysis purposes.

Finally in Figure 7 (c), the correlation between extreme wave height and extreme turret vertical motion has been shown. The results show some level of correlation between the two variables but as discussed before some variability mainly due to the variation of wave period associated with maximum wave height can be seen.

CONCLUDING REMARKS

This paper aims at reviewing the characteristics of global response of permanently moored FPSOs/FSOs in shallow water and revisiting the inputs to the riser analysis. The main conclusions are listed below:

- The comments made here are based on one example. However, based on authors' experience with the analysis and design of mooring system for several shallow water FPSOs, the main observations are dictated by the basic response of the system and can be extended to other systems.

- As shown here, the assumption used in the uncoupled riser analysis that maximum wave height and maximum vessel quasi-static offset coincide is very conservative. In the author's experience using this approach can lead to requirements for very heavy riser structures, more complex riser configurations, and have a large impact on the FSO hull, turret and mooring system, all leading to increases in CAPEX.

- The vessel offset is a function of wave group intensity and the large wave group may not contain the individual wave with the maximum wave height. Moreover, a singular large wave does not cause a significant offset. Therefore, the maximum offset is not typically caused by the maximum wave height.

- The natural response of the mooring system typically causes a lag between the extreme offset and the largest wave height in the wave group forcing the extreme offset. As a result, the peaks of offset and wave height do not necessarily coincide.

- The statistical analysis performed here using 50 numerically generated realizations confirmed the qualitative observations made from the model test data. Specifically, it has been confirmed that the peaks of wave height and vessel offset do not regularly coincide and the extreme values of the two variables are not correlated.

- Based on the results shown here, it is recommended to combine the MPM (or expected maximum) quasi-static offset with the significant wave height and the MPM wave height with the significant offset for uncoupled riser analysis purposes. This is in-line with the way the total response is calculated from LF and WF contributions for the global mooring response calculation purposes.

- As expected, the wave period plays an important role in vessel WF response. Therefore, attention has to be paid to the wave period associated with the wave height, specifically in regular wave riser analysis.

- This paper illustrates the importance of understanding the physics associated with the system dynamics before embarking on riser analysis and design. As mooring design (and FSO global analysis) and the riser analysis and design are typically performed by different entities, the definition of the offsets and the proper translation of them from global analysis output to riser analysis input is a critical interfaces during project execution that needs to be recognized by the end user when defining mooring and riser requirements, and ensuring consistency between them. This is also important when defining interfaces between mooring and riser teams in projects. It is quite common to restrict mooring offsets to a pre-determined value to serve as an extreme interface offset for the riser system design. As demonstrated in this paper this offset would be defined by the MPM quasi-static offset (mean + LF) and should be combined with the significant wave, rather than the maximum wave for shallow water systems.

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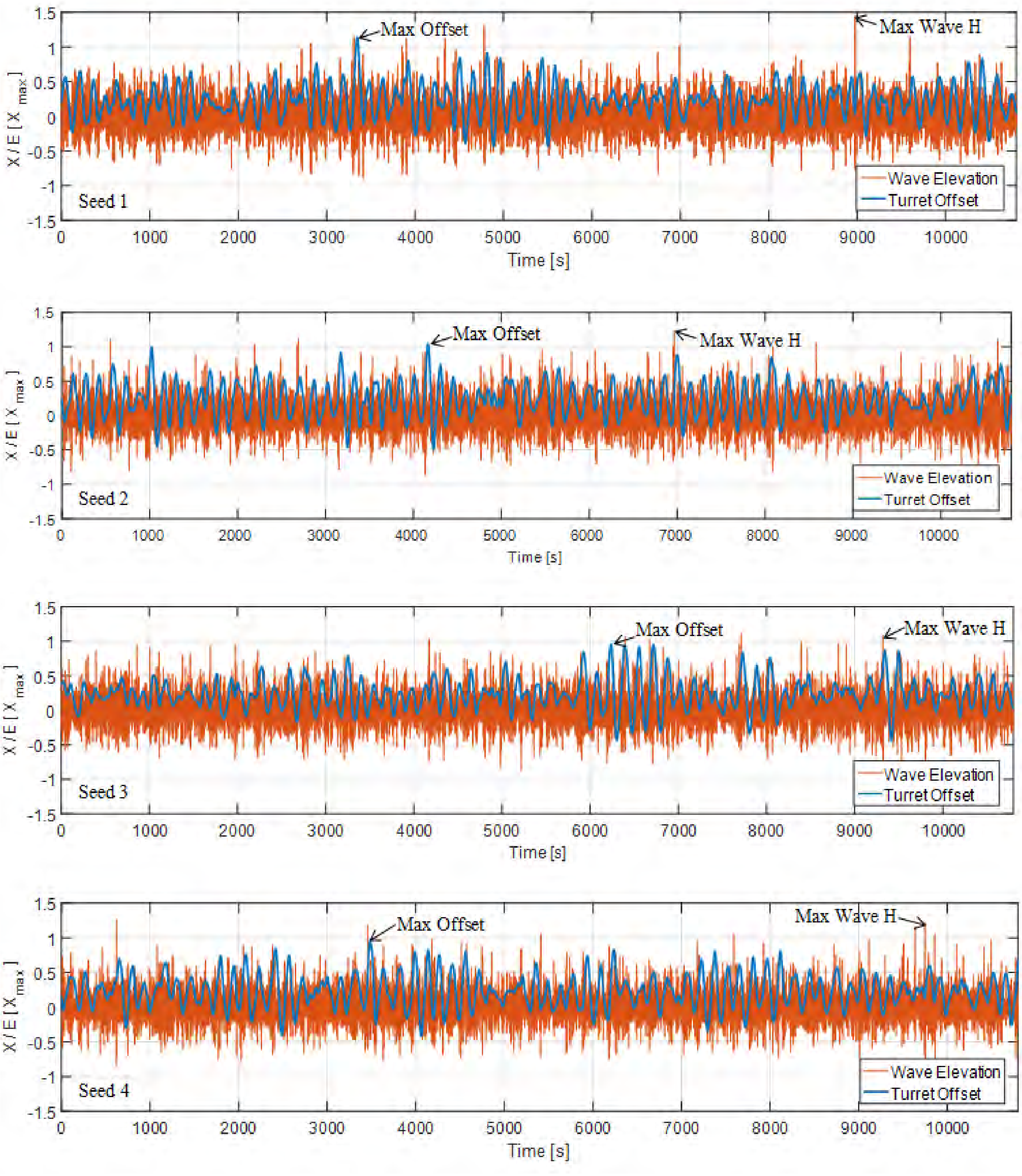
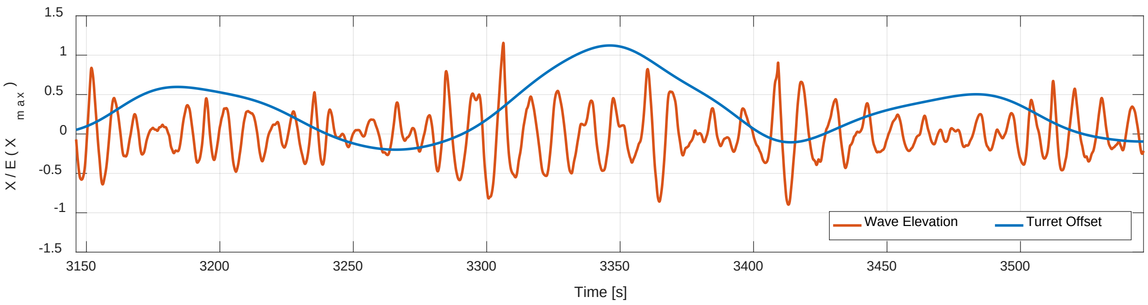
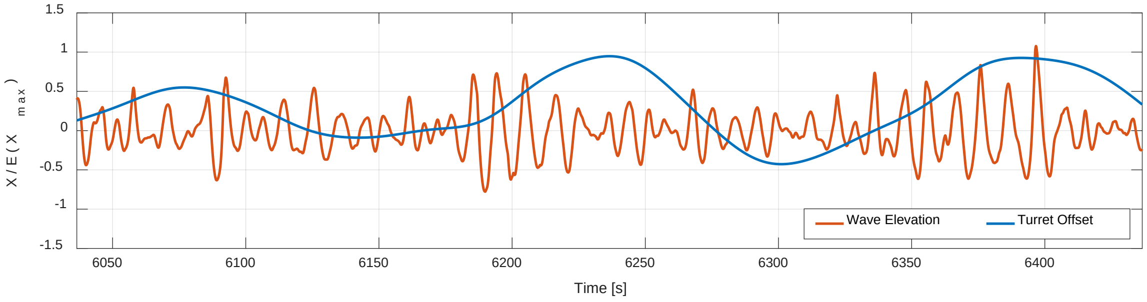


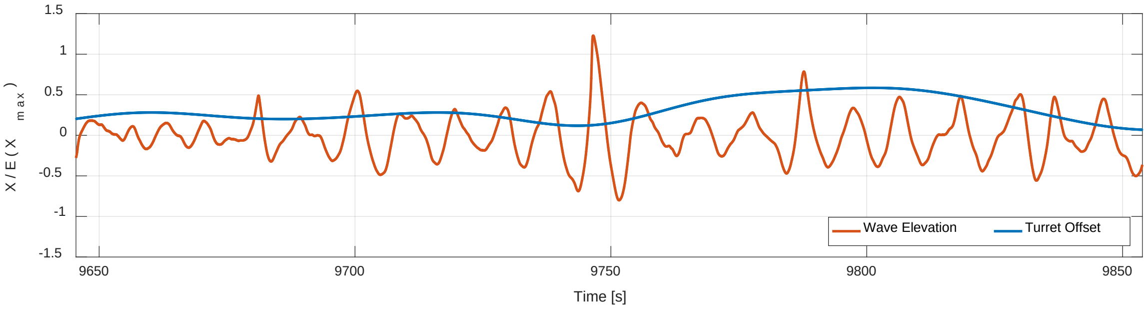
Figure 3 Normalized vessel offset and wave elevation



Seed 1 – Max Offset



Seed 3 – Max Offset



Seed 4 – Max Wave Height

Figure 4 Examples of maximum offset and maximum wave height incidents

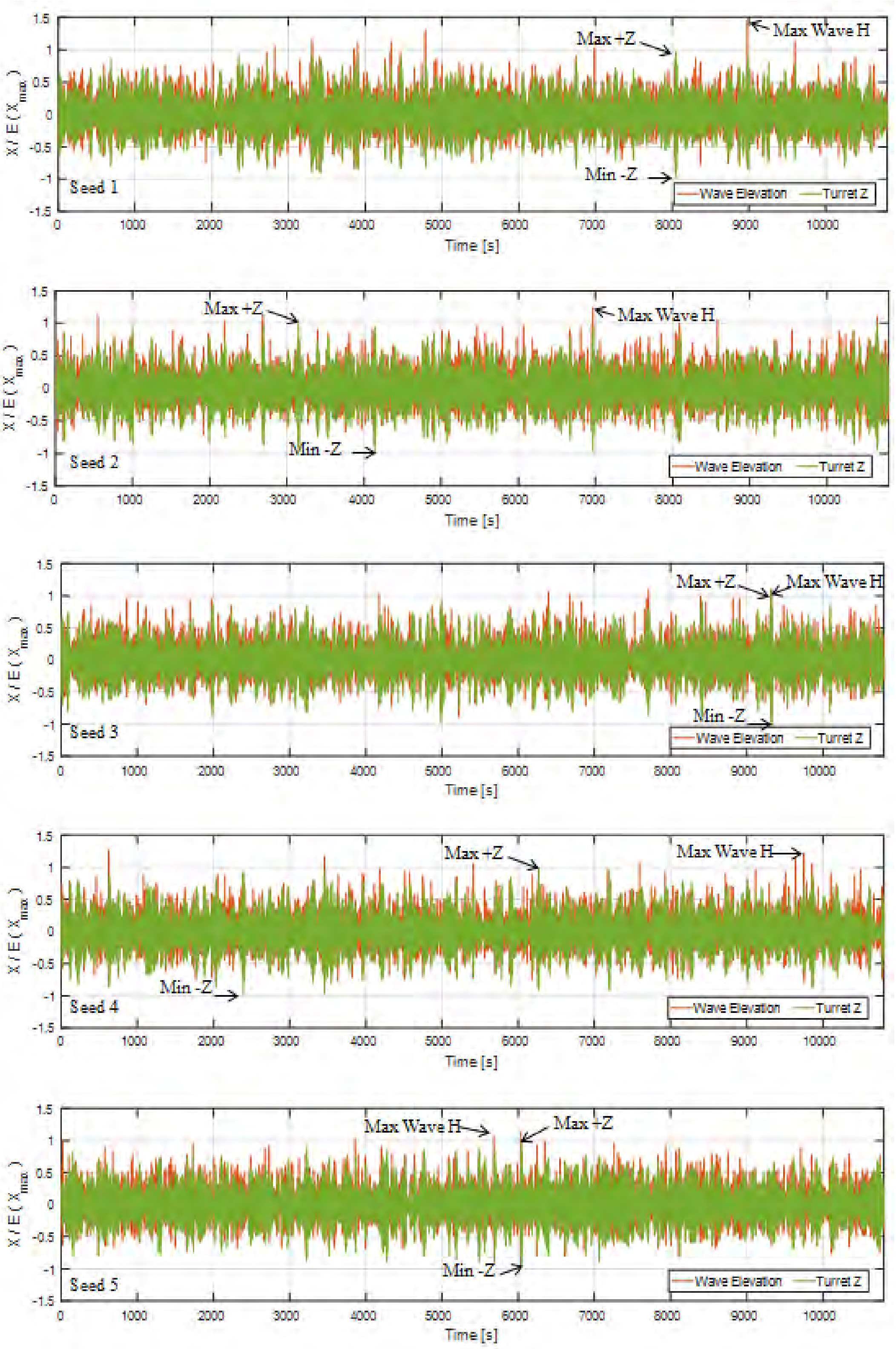
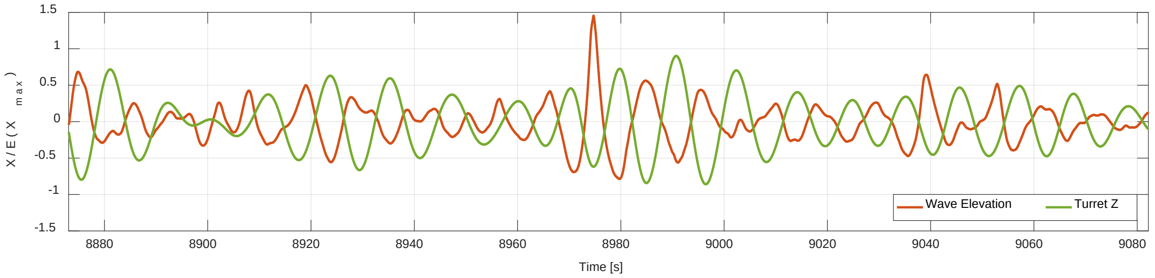
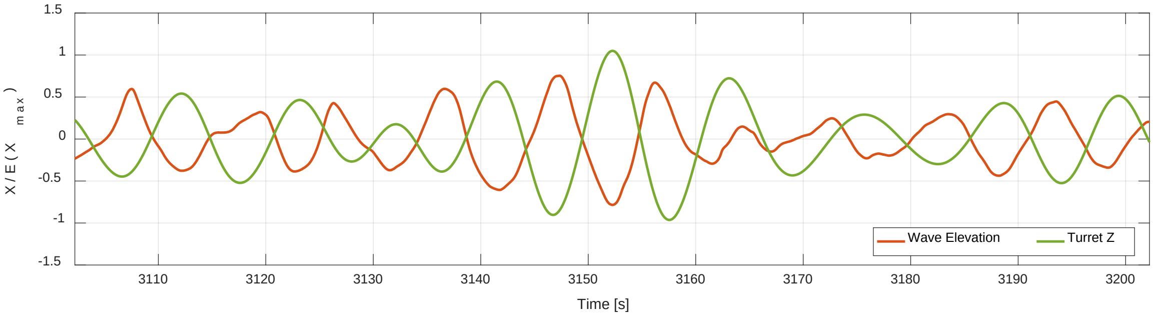


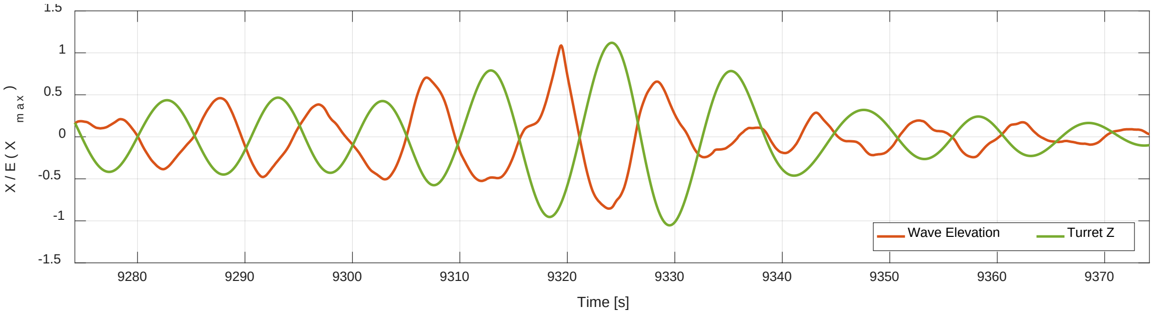
Figure 5 Normalized turret vertical motion and wave elevation



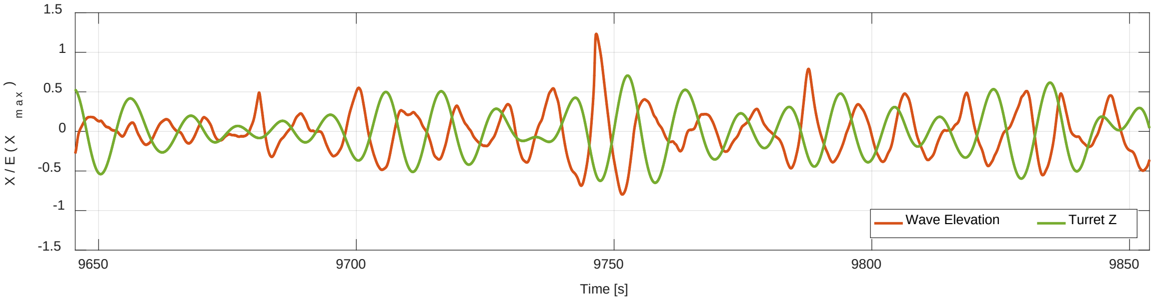
Seed 1 – Max Wave Height



Seed 2 – Max Turret Z

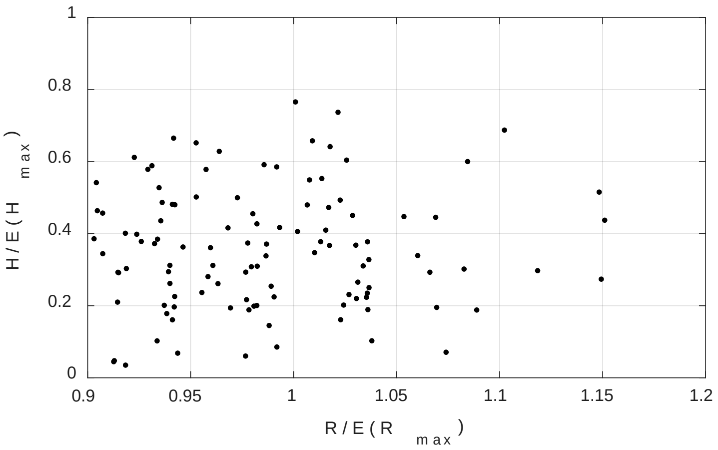


Seed 3 – Max Turret Z and Max Wave Height

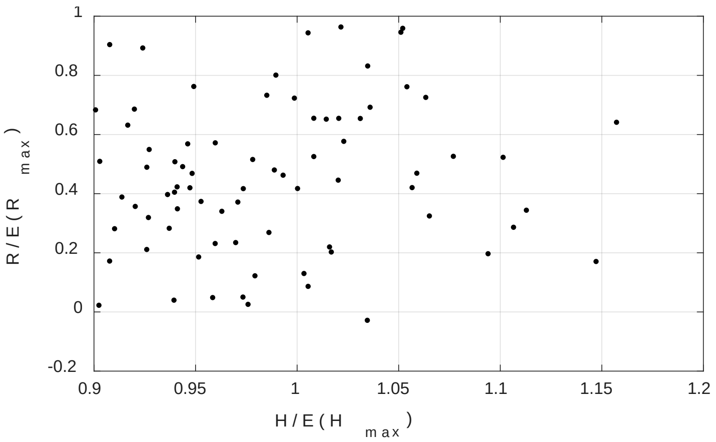


Seed 5 – Max Wave Height

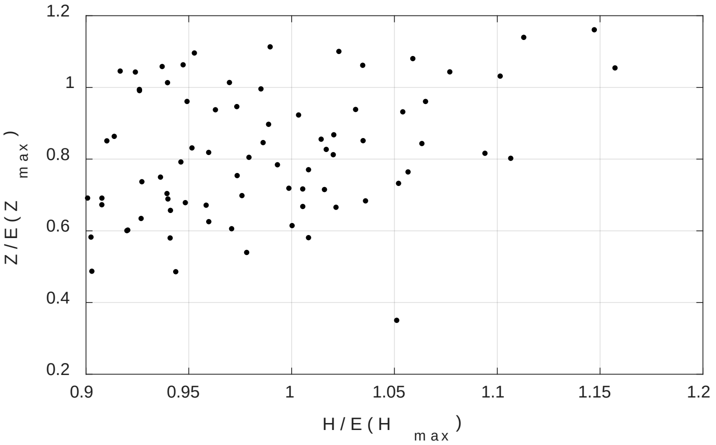
Figure 6 Examples of maximum turret vertical motion and maximum wave height incidents



Maximum offset and associated wave height



Maximum wave height and associated offset



Maximum wave height and associated turret vertical motion

Figure 7 Extreme events and associated values

Table 1 Extreme events and associated values

At Maximum Offset	Average of Associated Wave Height	
	E (H) / E (Hmax)	E (H) / Hs
	0.36	0.65

At Maximum Wave Height	Average of Associated Offset	
	E (R) / E (Rmax)	E (R) / Rs
	0.48	0.62