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RESPONSE OF A CALM BUOY MOORED VESSEL IN SQUALL CONDITION

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ABSTRACT

This paper reviews the response of a hawser moored vessel to squalls and addresses a novel method for obtaining statistically reliable design loads. Industry paradigms related to squall selection for analysis input are reviewed and renewed.

A benchmark database consisting of more than 15,000 unique squall-wave-current induced extreme values enables the validation of a range of less computationally demanding analysis and squall selection methods.

Extreme values are extrapolated to a design value using a Peak Over Threshold (POT) method to fit a Generalized Pareto Distribution (GPD). The influence of associated metocean conditions and squall characteristics on the vessel response is presented. By means of bootstrapping a satisfactory population size for design purposes is studied. The findings challenge common design practices currently employed throughout the industry.

Keywords: *Squalls, CALM Buoy Mooring, Offloading, Response Based Analysis.*

INTRODUCTION

A squall line is a term used for the indication of a number of active thunderstorm cells that organize in a mesoscale line, which as a system can last for several hours [1]. These lines can be hundreds of kilometers long and move perpendicular to their orientation. They are associated with an advancing cold front that meets warm air. Since the density of the cold air is higher that of the warm air, it pushes the warm air upwards. As the warm air travels upwards, water vapor starts to condense, making the air lighter and accelerating it upward even further. This means that at the leading edge of the line multiple chaotic updrafts are formed, causing independent gusts or squalls to form locally. Squalls are commonly associated with heavy rainfall, hail and lightning. The peak wind speed of the squall can reach up to 50 m/s and is often observed to be associated with a wind direction change. They have been observed in many regions, the areas of interest where squalls occur and FPSOs are moored are West-Africa and South-East Asia.

Squalls have become a major driver of mooring design more recently, as squall time traces become progressively available for incorporation in mooring analysis. It has been found that for the aforementioned regions squalls can very well lead to governing design conditions. Due to the nature of squalls, rapidly increasing wind speed and change of heading, the response of a moored vessel is transient, meaning that it should therefore be a dynamic non-steady state load case and should be performed in a time-domain analysis. In the past decade a strong focus has been on squalls in West-Africa region where FPSOs are commonly spread moored ([2–5]). Issuess with squall scaling have lead to adoption of response based analyses, where the response is extrapolated to a design value instead of the input (metocean). More recently focus has shifted towards turret moored vessels ([6–9]), yielding issues with a vessels' relative heading before the squall commences. The dynamic response of the vessel to the squall event is greatly dominated by the relative heading during the impact of the high wind peak(s). A squall that hits the beam of the vessel, with much more wind area, gives a significant different response than the same squall time trace applied to the bow. Furthermore, due to the inherent dynamics of squall response, factors such as yaw rate damping and wave drift damping influence the response of such transient systems greatly. It is noted that, perhaps counter intuitively, higher wave and current conditions may very well result in lower extreme mooring loads due to the wave drift damping effects.

Not all guidelines provide assistance in dealing with squalls. The codes that do (DNV-OS-E301, API RP 2SK) recommend to scale the squall as conventionally is done with waves, wind and current. However, scaling to a certain peak wind speed may be wrong for a number of reasons. The squall wind speed is transient, not steady-state and very chaotic (not well understood) of nature, which makes it difficult to extrapolate and results in unknown levels of confidence. This means that the extrapolated peak wind speed may not be realistic from a meteorological point of view, as the physical drivers to the gust front may not be scaled right. As suggested by a number of papers recently (e.g. [4]), a response based analysis where the output of the mooring analysis is extrapolated, and the squall time traces are not manipulated. Response based analysis for mooring systems is not new and has been introduced before for regular storms, see for instance [10]. This type of analysis is possible if a well-defined record is available for the area of interest, which is more common nowadays but far from available for all sites.

The main disadvantage of a response based analysis is that the engineer should be confident that the range of simulations contain governing response characteristics. As the response is extrapolated instead of the input, it should contain sufficient cases and well capture the extreme behavior of the system.

Contrary to conventional storms, squalls are much more difficult to predict over a longer period. Measurement of squall lines requires technically advanced Doppler radar systems specifically designed for this application. As the wind behavior in a squall is very chaotic, predicting peak speed and rate of change remains difficult. For weather restricted operations, such as offloading of tankers at a terminal or FPSO, the sudden appearance of a squall could cause undesirable, or even dangerous events.

Spread moored vessels have stiffness due to the mooring system in all three horizontal degrees of freedom: surge, sway and yaw. Turret moored vessels are less limited as they are allowed to weathervane and thus can yaw relatively freely, the motion being damped by the rate of turn of the vessel. For hawser moored vessels, such as offloading tankers at an FPSO or terminal, the mooring system is even more permissive: it limits the motion of the vessel in one degree of freedom, in line with the hawser (usually the surge motion). This degree of freedom is, however, only restricted in one direction of the line (the line cannot take compression). The stiffness curve of a hawser mooring system is furthermore highly non-linear. Due to these strong non-linear and discontinuous characteristics in combination with the transient nature of the squalls, the response of such a system is very difficult to define, making it difficult to define *a priori* a selection of potential governing load cases.

Conventional methods related to steady state conditions, normal storm conditions for example, are straightforward in selecting wind conditions and associated wave and current conditions. Typically load case combinations assess maximum and minimum influence of one variable within a certain likelihood. This minimum and maximum are straightforward; i.e. related to maximum and minimum values of wave height, wind speed or current speed. For squall governed regions the process is not so straightforward due to the transient behavior. Suggested methods in the industry currently advocate a similar approach in which a small set of *relative high peak wind speed* squalls are selected and subsequently scaled to meet maximum wind speeds as found in the extreme values found in metocean data reports. This paper challenges current design philosophy, as it was found in the studies presented here that squalls with the highest peak velocity do not automatically lead to governing cases.

To support this claim, this paper presents the results of a numerical mooring response study of a large calm-buoy-hawser-moored vessel subjected a large number of squall time traces (242) measured offshore near the location of interest. Instead of scaling the squalls to extreme values with given return periods, they are ran as measured and the results obtained are scaled to the design return period (response based analysis). For every squall associated p50 current and p50 wave combinations are defined for 8 headings each, resulting in 64 load case combinations per squall set. In total almost 15,500 cases have been analyzed. The Ariane7 mooring analysis suite developed by Bureau Veritas has been used. As a key alternative tug support with a constant bollard pull on the stern of the tanker is assessed.

METHODOLOGY

Mooring Analysis

In order to obtain statistically converging results in a response based analysis, it is key to use a large dataset. The available dataset contained 242 squalls, identified by a threshold wind speed from five years of measurement. As squall phenomena are uncorrelated to ambient wave and current conditions, these should be varied in direction and amplitude in order establish the generation of a statistically valid dataset. The associated wave and current loads are of high relevance since they partly define the initial location and orientation of the vessel, which has a significant impact on the maximum hawser loads during a later stage of the squall. In this study p50 conditions are used for the ambient current and waves. Note that no seed variation is carried out for the waves, as the response is governed by squall loading the waves merely determine the intial position. A sensitivity check is carried out for p10 and p90 criteria, with a selection of governing cases. There are two strong arguments in favor of using the p50 conditions over the p10 and p90: they better represent day-to-day conditions and are relatively benign. Mild waves and current are expected to lead to higher squall induced loads, since these loads will dampen the motion of the vessel, contrary to a mooring system with stiffness in all directions, as the vessel is allowed to build up momentum.

The significant wave height and associated zero crossing period, and current velocity are selected for the specific month the squall took place. In total eight (45 degree directional bins) independent wave and current headings are defined. For each squall this leads to 64 mooring response simulations carried out. The probability of each of the 64 wave and current combinations (for each month) is found by basic joint-probability calculation; multiplication of individual likelihood.

For each of the 242 squall time traces now 64 individual cases are defined, leading to a grand total of 15,488 cases to be analysed. In order to enable simulation of such a vast batch, a number of assumptions are made. Mooring line dynamics are neglected, allowing a quasi-static method based on catenary geometry to be adopted. From each simulation the maximum loads per mooring line and hawser are extracted. Note that direct use of the maximum is applied as now MPM or other extreme value can be fitted to a single squall event. Combining these maxima with their associated joint probability enables the generation of a probabilistic distribution, which can be extrapolated to the respective design value. This distribution describes the probability of load exceedance in a single squall event. Based on the assumption that the 242 squalls give a good resemblance of typical squall events in that area, and that the p50 wave and current conditions result in a realistic associated condition. The methodology for generation of the mooring response is summarized in the flow chart of Figure 1.

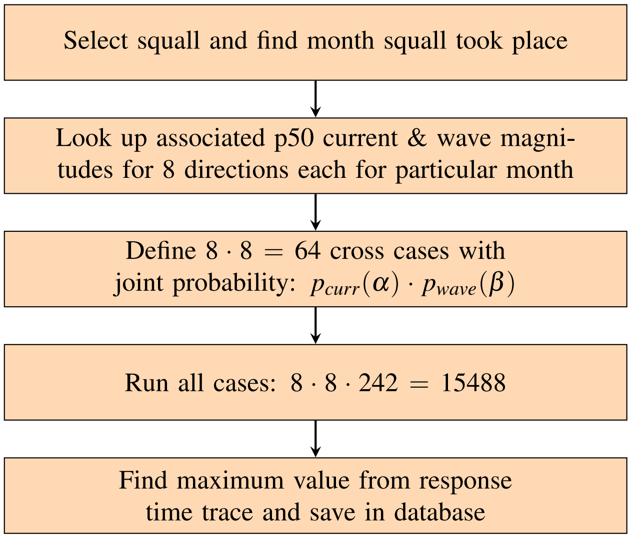

FIGURE 1. FLOW CHART MOORING ANALYSIS AND ASSOCIATED PROBABILITIES

Design Value Estimation

The mooring system and its response is highly non-linear and can be non-continuous. The vessel can build up momentum and speed depending on the initial vessel heading relative to the squall wind speed direction. It may thus be assumed that the extreme value behavior is fundamentally different from the average response in turn leading to preference of a Peak Over Threshold (POT) method compared to a method utilizing the complete dataset. A threshold is defined and for loads larger than said threshold a distribution is fitted. This threshold is chosen such that only extreme behavior within the maxima is taken into consideration. According to [11] the family of distributions belonging to threshold extreme value excess is that of the Generalized Pareto. The Generalized Pareto is fitted to the excess data, i.e. the data larger than the threshold. This distribution captures the asymptotic characteristics of the tail of a Generalized Extreme Value distribution, which would be fitted to the entire dataset of extrema. However, due to the nonlinearities and the specific interest in the tail, it is much more accurate to fit a distribution to the tail only. The distribution is fitted with a maximum log-likelihood estimator. This estimator is numerically maximized.

Selection of a threshold for extreme value analysis is commonly subject of debate, as it is highly subjective. Results of a threshold study for the entire database of squalls is presented in this paper, by means of plotting the mean excess to a selection of thresholds. The distribution is valid for excess of the selected threshold, but should be equally valid for thresholds larger than the selected one. This can be learned from the mean excess plot, where this characteristic shows itself in linearity; where the Pareto distribution is valid the graph is linear. Of course this holds only for a sufficient number of extrema taken into consideration.

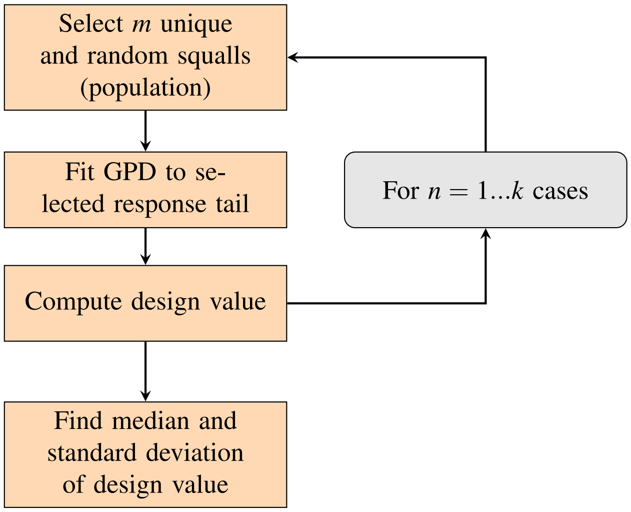

FIGURE 2. FLOW CHART BOOTSTRAPPING FOR k REPETITIONS AND m SIZE POPULATION

In this study the number of squalls required for a representative database (statistical convergence) is studied by means of bootstrapping. A selection is taken from the database, of a number of squalls, starting with a low number (for instance five or ten containing each 64 responses) and stepwise increased to the total number in the database (yielding only one unique set of squalls). By means of a Monte Carlo analysis a large number (in order of thousands of cases) of design values is generated for a random but unique selection of that number of squalls. The design values are computed as described above, with a threshold that is found satisfactory for that range of unique squalls. In order to have a fair comparison between loads, the hawser loads are considered and not the mooring lines (since these can be loaded in various directions, ranging from in-line to between-line loads). The threshold cannot be defined and studied for each individual case in the Monte Carlo analysis, as this would require extensive hand work. Therefore beforehand per selection of number of squalls a threshold has been defined. For a low number, the threshold is lower (as the odds of not having squalls with high loads is significant). The threshold increases until it reaches the value used for the entire database. The median, maximum and standard deviation of the design value is generated for each unique squall number taken into consideration.

A second database is generated where a tug has been introduced that pulls with a constant bollard pull on the stern of the vessel. Often tugs are used to tension the mooring system during offloading operations, to mitigate for high loads occurring during fishtailing. The effect of the tug on the hawser loads is studied and compared to the case where no tug is used. The tug strategy is to simply pull straight aft of the stern of the vessel.

ANALYSIS

Modeling and Assumptions

The vessel hydrodynamic database is generated with AQWA radiation-diffraction software. All Quadratic Transfer Functions (QTFs) terms (including off diagonal terms) of the second order drift loads are computed as well with this software. The CALM buoy is modelled as a morison element with buoayancy based on instantaneous submergence and is not modelled as a diffracting element, which would lead to overestimation of hydrodynamic loads.

For the time domain mooring analysis Ariane7, developed by Bureau Veritas, is used. This program is very quick and efficient, enabling the generation of a large dataset of results. The speed of computations comes at a cost of a number of assumptions. For instance, mooring line dynamics are neglected and are calculated based on an instantaneous catenary shape (i.e. no drag loads, seabed friction or snatching takes place). The hawser is modeled as a load which is a function of the instantaneous distance between the vessel and buoy fairleads, taking into account non-linearities in stiffness. Secondly, first and second order motions are decoupled. The mean position of the vessel is computed based on wind, current, asymptotic added mass and damping, and drift loads. First order motions are superimposed to this slow motion by means of displacement RAOs. Wind and current loads are computed based on a drag formulation. Lastly, the buoy hydrodynamics are simplified to a floating element with drag loads (with respect to current and relative motions).

All squall cases are also carried out with a simplified tug model. In order to keep simulations efficient, the tug has been simplified from a hydrodynamic body to a constant force of 50 tonnes placed on the stern of the vessel, always pointing away from the vessel (parallel to center line). The effect of the squall on the tug is thus neglected. This is acceptable, as the tug driver is not considered as well, who likely anticipates and aims to keep his vessel in the aforementioned position. The simplified model should sufficiently provide the effect of having a tug in place pulling with constant throttle and aiming to tension the hawser system.

Mooring System

The mooring system consists of a CALM buoy terminal moored in relatively shallow water (65m). The sea bed is assumed to be flat. The buoy is moored with a symmetric three leg catenary system made of chain. A VLCC type tanker is moored to this buoy with a flexible hawser. See figure 3 for a schematic overview of the system. The area of interest is a tropical region, where squalls are regularly observed, between 10° S and 10° N, where otherwise conditions are relatively benign.

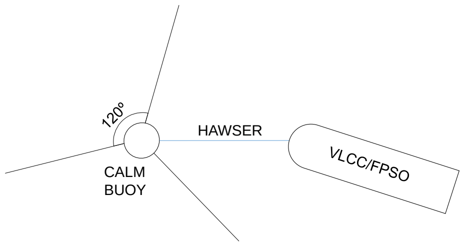

FIGURE 3. MOORING SYSTEM LAYOUT: CALM BUOY, HAWSER AND TANKER

Vessel Characteristics

The vessel assessed in the current paper may be described as a purpose built, non-ship-shaped, FPSO with relatively common topsides and windage areas compared to main characteristics. The vessel L/B ration is relatively large at value over 6.5 and B/T ratios are within common ranges. The large L/B ratio may result in high yaw inertia and associated yaw resistance due to drag effects. The vessel has been moored to a calm buoy in water depths of around 2.5 to 3.0 of the maximum draft. The shallow water effects are therefore quite insignificant.

Metocean Conditions

P50 monthly significant wave height and corresponding zero crossing periods are used per direction as input to the analysis. The directional probability provides the probability of that case. Even though some cases contain a zero probability of occurrence, they are still computed in order to keep post-processing efficient. Similarly to wave, the p50 conditions are used for current speeds, along with directional probabilities. The wave conditions are benign in the summer and worse during winter: the p50 significant wave height is maximum in November, with a value of 2.5m. In figure 4 the significant wave height (upper part) and probability (lower part) is presented to the direction and month. Current is relatively constant over the year, with peaks up to 0.36 m/s. Figure 5 provides an indication of current speeds and probability per month and direction.

A check is carried out with p10 and p90 metocean criteria. The wave height and speeds vary in the range of 30% from the p50 values.

Statistics

A GPD (Generalized Pareto Distribution) is fitted to a selection of extrema by maximizing the log likelyhood. The distribution parameters of the following equation [11] are found:

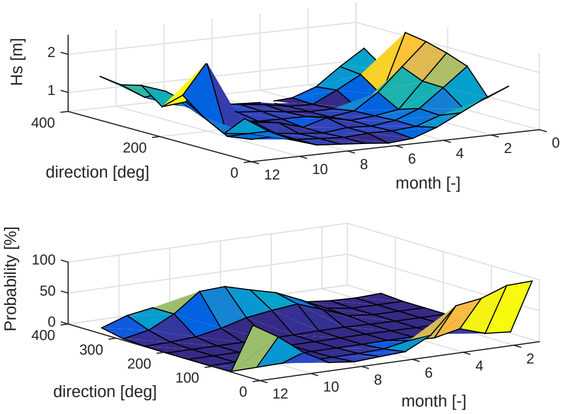

FIGURE 4. P50 WAVES SIGNIFICANT WAVE HEIGHT AND PROBABILITY

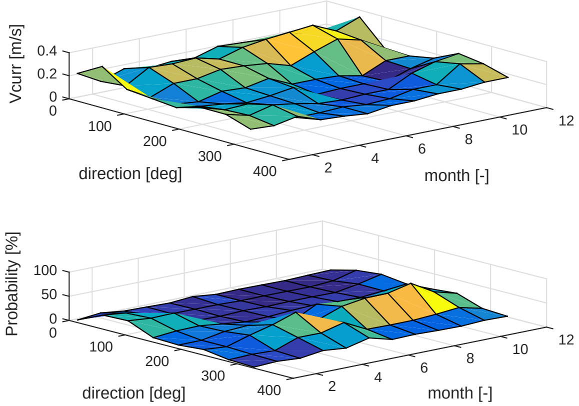

FIGURE 5. P50 CURRENT SPEED AND PROBABILITY

$$P\{X > x\} = \zeta_u \left(1 + \xi \frac{x-u}{\sigma}\right)^{-\frac{1}{\xi}} \tag{1}$$

Where σ denotes the scale parameter, ξ the shape parameter and u the threshold. The last parameter is defined as the probability of exceedance of the threshold: $\zeta_u = P\{X > u\}$.
The parameters are fitted and a return level can be computed. An estimated 50 squalls occur per year, leading to the following equation:

$$x_N = u + \frac{\sigma}{\xi}\left[(50N\zeta_u)^{\xi} - 1\right] \tag{2}$$

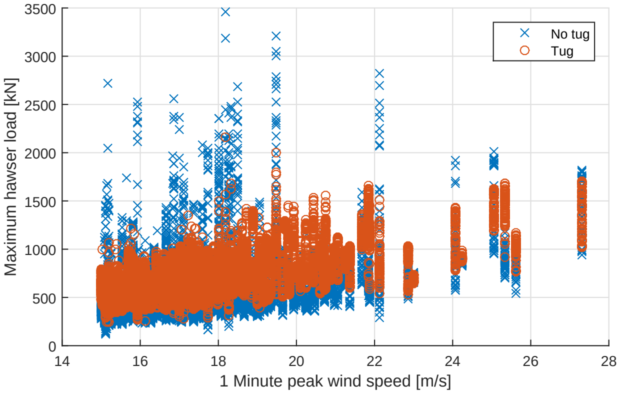

FIGURE 6. EXTREME HAWSER LOADS TO 1 MINUTE PEAK SQUALL VELOCITY

Where N denotes the return period in years and x_N the return level.

RESULTS

Hawser loads are presented as a function of one minute peak wind velocities in Figure 6. It can be seen here that the highest peak velocity does not necessarily give the highest response, especially when no tug is present. Even more so, one of the cases with one of the lowest peak wind speeds (squall 92) causes one of the highest loads. This is due to the fact that when this specific squall hits the stern of the vessel for a specific combination waves and current, causing the vessel to accelerate and sail over the buoy, leading to high peak loads in the hawser.

Once a tug is considered the spread of the results significantly decreases. For the case of squall 92 the vessel does not sail over the buoy anymore. Even though the tug is modeled as a simple constant load, tensioning of the mooring system mitigates the vessel building up momentum.

Peak wind speed and direction of two of the governing squalls in the no tug cases is shown in Figure 7. Rate of change of velocity is relatively high, but not the largest of all squalls. Furthermore, the change in direction for one squall is relatively small.

Threshold Selection

Threshold selection is studied by plotting the mean excess to varying thresholds. Results for the no tug (upper figure) and tug (lower figure) cases are shown in Figure 8. [11] advises to look for a linear increase in these plots, and define the threshold close to the start of this linear line segment.

For both cases we see a linear increase at thresholds between approximately 400 to 1000 kN. However, for larger thresholds characteristics differ: the hawser load excess generated without a tug in place increases further (albeit relatively flat), indicating a threshold value of 1200 to 1700 kN is valid. For values larger than this threshold too little extremes exist for a valid distribution model fit. These curves clearly indicate the system characteristics, showing a well visible change in behaviour at approximately 1000 kN. It is important to include this in the extrapolation of a design value.

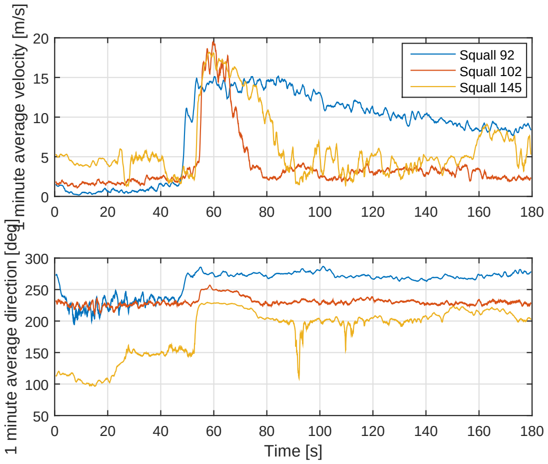

FIGURE 7. GOVERNING SQUALL TIME TRACES

In the tug cases we see a plateau after which the excess decreases - the number of extremes above these threshold becomes very small, leading to inaccurate results for tug load cases for thresholds larger than 1200 kN. In the tug load case we select a threshold of 500 kN, which should yield conservative results.

The effect of a threshold that is too small is shown in the left part of Figure 9. In this figure the extremes above threshold for the cases without a tug are shown with the fitted GPD. In the right part of this figure a better threshold is chosen, being able to better capture the characteristics of the system.

Bootstrapping

The design value is computed for various random and unique squall population sizes within the database. In the Monte Carlo simulation the design load is distributed. Therefore the median and mean value, in combination with the standard deviation are regarded. See figure 10 for an example distribution, where 10 squalls are selected from the database of tug results 500 times and design values are computed (note that extremes above 3000 kN exist but are not shown, as this figure would otherwise become unclear).

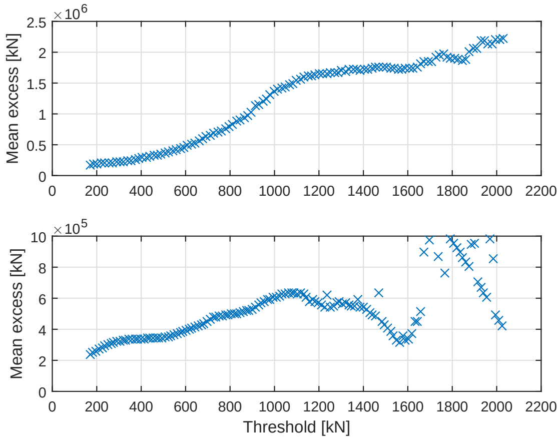

FIGURE 8. MEAN EXCESS FOR VARIOUS THRESHOLD VALUES (NO TUG UPPER, TUG LOWER FIGURE)

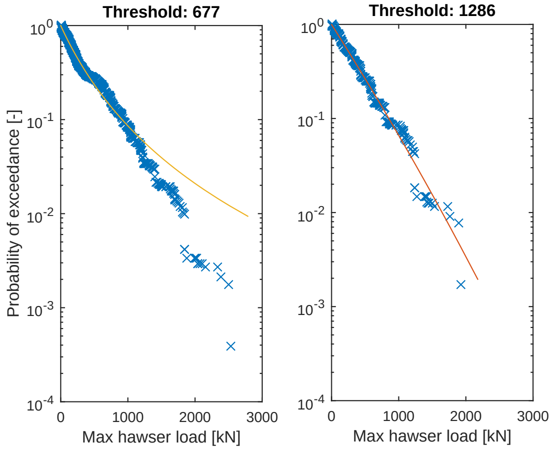

FIGURE 9. EXAMPLE GOODNESS OF FITS FOR TWO THRESHOLDS (NO TUG SITUATION)

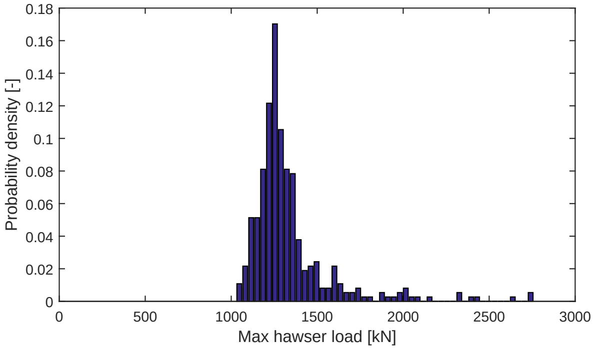

FIGURE 10. HISTOGRAM OF DESIGN LOADS IN MONTE CARLO SIMULATION FOR ONE POPULATION SIZE OF UNIQUE SQUALLS)

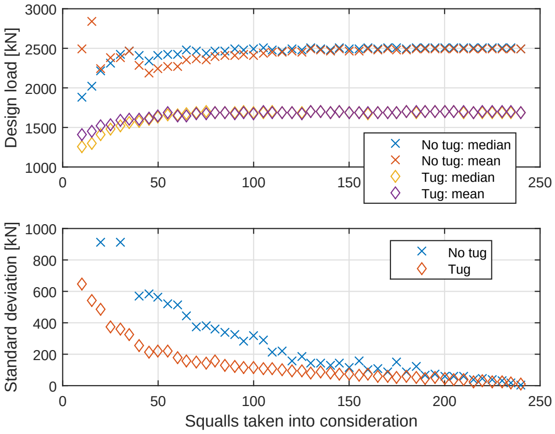

FIGURE 11. MEDIAN, MEAN AND STANDARD DEVIATION OF DESIGN LOAD FOR VARIOUS SQUALL POPULATION SIZES)

Obtained median, mean and standard deviation values for various squall population sizes are presented in figure 11. The median and mean are presented in the upper part of this figure for both tug and no tug situations. The design value with a tug in place is significantly lower and shows less spread when the selection is relatively small, contrary to the no tug case, where a selection of less than 50 squalls yields erratic results. In the lower figure the standard deviation of the design load is presented. The standard deviation of the cases where a simple tug has been considered, show significantly less spread than the cases where no tug is modeled. This was also indicated by figure 6, where the spread of both situations can be observed.

Different characteristics can be observed in the decreasing standard deviation: first it decreases quickly and non-linear, after more than 100 squalls in the population the decrease becomes somewhat linear. The first part of the decrease is caused by statistical convergence of the results, and the latter is an effect of decreasing variance in the the squall selection; the populations start to get similar due to many of the same squalls being selected between the Monte Carlo cases.

This implies that when considering the offloading at a terminal with a tug, a smaller selection of squalls is required: approximately 75 squalls in the population yield a standard deviation below 10% of the design value. For the cases with no tug this point occurs for population sizes slightly larger than 100 cases. In these points the mean and median design values also become approximately equal.

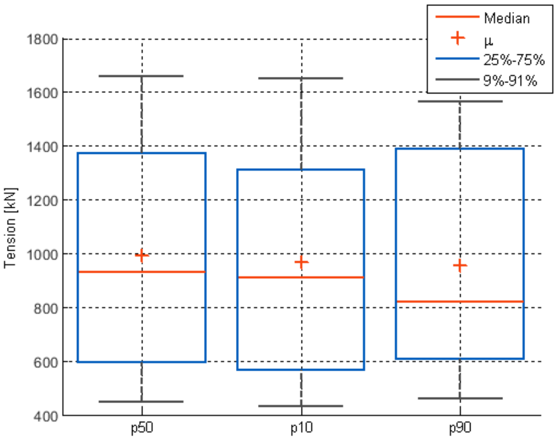

FIGURE 12. MEDIAN, MEAN AND STANDARD DEVIATION OF DESIGN LOAD FOR VARIOUS SQUALL POPULATION SIZES)

Sensitivity of ambient wave and current conditions

The sensitivity to using p10, p50 or p90 associated metocean criteria is studied. Since the associated waves and current partly define the initial position of the vessel (which plays a dominant role in the transient squall responses), they can be of large influence. It was assumed that using p50 criteria would be sufficient to capture well the daily conditions. To check this assumption, a number of cases is carried out with p10 or p90 waves and current. The found hawser loads are compared to those of the p50 cases.

Not all 242 squall populations are ran with p10 and p90 criteria, but a selection is made. Six governing squalls are identified and ran. The results of these simulations are presented in Figure 12 in boxplot format. This figure shows that statically speaking the difference is negligible. Likely this is because both current and waves are either lower or higher in amplitude, causing a similar initial position of the vessel. Using p50 associated wave and current criteria is thus a good assumption

CONCLUSION

Based on the material, figure 11 and others, presented it may be concluded that proper convergence has been found in the determination of a well-supported squall governed design load using the response based method and the utilization of day-to-day conditions by means of p50 ambient wave and current criteria. The total amount of squall input events required to obtain high confidence design values has been shown to be far less than the 242 events as used in the current assessment.

Even for the selected 242 squall events it has been found, by observation of figure 6, that the threshold value of approximately 15 m/s 1 minute peak wind speed is considered high and the data suggests a lower threshold value can be advocated. Furthermore, most squalls are found with relatively lower wind speeds, where also highest loads are observed (due to the big spread of cases and ambient criteria here). This indicates that rather a big dataset leads to governing design cases instead of a selection based on peak wind speed or other parameters. Good extrapolation of a design value can already be carried out from these relative low peak wind speed squalls. An important advantage of the presented method is that it's not dependable on a designer and likelyhood of missing important load cases.

The load threshold for fitting of the GPD has a large influence on the found design value. The mean excess curve shows clearly the difference in response characteristics. As mooring analysis is carried out for systems that differ in stiffness and other properties, it is important to study the threshold well for the particular system as response characteristics likely differ as well.

Based on the results presented in figure 8 it may be concluded that methods normally used in defining proper threshold values for defining the data set to which the GPD is fit result in design values of good confidence, as visually indicated by figure 9. Considering that a median value is a more suitable choice to use in an MPM determination we find that for the no-tug case convergence within 3-5% is obtained from 50 or more squall events while less cases clearly indicate erratic results. For the tug assisted cases a more gradual behavior—resulting from the absence of any non-continuous type of events—is observed, however, the overall number of squalls appears to remain approximately equal. Given that the database is generated for a single vessel, loading condition and metocean location, it may be agreed some margin is to be included in the amount of squalls to be considered suitable for design load determination. Therefore a more conservative number of 75-100 seems appropriate. It is recommended to repeat the presented analysis for various vessels and sites in order to better understand the effect these parameters have on the methodology.

From a more operational point of view it is interesting to observe the significant design load reduction resulting from the tug assistance. It is noted, however, that the bollard pull setting and the windage area in combination with wind peak speeds are to be selected such that the extreme behavior observed in the no-tug cases is avoided. This means that a slack hawser condition should be avoided for the above conclusion to hold.

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