Extreme Wave Effects on Deep Water TLPs
Lessons Learned from the Snorre A Model Tests

T.B.Johannessen (Aker Kværner Engineering & Technology)[1], S.Haver (Statoil),
T.Bunnik & B.Buchner (MARIN)

Abstract

In the last few years there has been an increasing focus within the shipping and offshore industry on extreme wave events and abnormal wave conditions. Hurricanes Rita and Katrina last year confirmed the importance of these extreme waves for all types of offshore structures. When they are not properly taken into account in the design, they can threaten the integrity and safety of a platform. Based on model tests and simulations on the Statoil operated Snorre A, the present paper discusses the following issues:

- Why should we focus on accidental wave events?
- How should we analyse them?
- How do we carefully take into account the inherent randomness of extreme waves?
- What are the available measures we can take in the design?
- What are the lessons learned for deepwater TLPs in hurricane conditions?

The paper discusses these issues based on an extensive series of model tests with the Snorre A. The airgap, wave loads and platform response were measured. The TLP was subjected to a range of wave height-wave period combinations and long time durations of storms were used to get sufficient insight in the statistics of the extremes.

Further numerical simulations were carried out with a Volume of Fluid (VoF) method coupled to a time domain simulation model. The VoF method computes the hydrodynamic loads, which are subsequently applied as external force in the motion model. The numerical simulations give a lot of insight in the loading and response process of TLPs.

[1] Corresponding Author: P.O.Box.222, 1326 Lysaker, Norway
Email: thomas-b.johannessen@akerkvaerner.com

Introduction

The Snorre A

The Snorre A was installed in the Tampen area in the Northern North Sea in 1992. The Snorre A was the third tension leg platform (TLP) to be installed after the Hutton TLP and the Jolliet TLP. The main particulars of the Snorre A are shown in Table 1 for a characteristic present loading condition at the mean sea level (MSL).

Displacement	108 491 Mt
Mass	80 754 Mt
Tether Tension	24340 Mt
Riser Tension	3397 Mt
Column c-c spacing	76 m
Column Diameter	25 m
Pontoon Height x Width	11.5 m x 11.5 m
Pontoon Bilge Radius	2.0 m
Underside of Double Bottom of Deck	64.5 m above keel
Water Depth	308 m
Draft	38.3 m
Natural period in Surge & Sway	84 s
Natural Period in Yaw	69 s
Natural Period in Heave	2.3 s
Natural Period in Roll & Pitch	2.4 s

Table 1 Snorre A Main Particulars at MSL

Figure 1 and Figure 2 show respectively an artist's impression and an aerial photo of the Snorre A as it stands today. The hull is tethered to the seabed via 16 steel tethers. The tethers are lead from the concrete foundations up through tether conduits inside the columns and terminated at the mooring flats above the sea surface level.

Figure 1 Artist's impression of the Snorre A

Figure 2 Recent aerial photo of the Snorre A

In 2003 the present operator, Statoil ASA, carried out a technical safety review for the Snorre A. Among other issues, tether integrity was identified as a subject that should be checked more thoroughly. There were a number of reasons for this:

- The design basis was changed in the mid-nineties. As will be discussed in a later section, tether slack was downgraded from a ULS limit to a practical limit similar to an SLS limit (ULS, ALS and SLS are explained later) in order to allow for an increased payload capacity. As a consequence, tethers will be more highly utilised in the governing tether slack scenario.
- In the original design, the characteristic wave induced loads were estimated using the most probable maximum in the 100-year sea state as the 100-year response. Since then it has been realised that this method will give a value lower than the 100 year target return period for the load effects. It is now common to use the 90% quantile in the governing seastate rather than the most probable maximum to obtain a more accurate estimate.
- Finally, the latest predictions of the Northern North Sea wave conditions corresponding to an annual exceedance probability of 10^{-4} are somewhat more severe than what was originally adopted.

In view of these subjects the concern was that there could be a larger probability of major wave-deck impacts than assumed in design. A major wave-deck impact will increase the tether loading considerably.

In order to ensure that the Snorre A is safe with respect to extreme tether loading, Aker Kværner carried out a comprehensive tether integrity reanalysis study in 2003 and 2004. The study included a large model testing programme carried out at the facilities of MARIN in the Netherlands together with extensive analysis work, the establishment of an updated operational weight margin and the evaluation of tether response to slack events. A main object of the present paper is to present how the model test experiment was designed in order to cope with both an extremely complicated loading mechanism and the inherent simultaneous behaviour of the various dynamic component processes.

Badly Behaved Problem Types

In addition to the presentation of the Snorre A model testing activity, the purpose of the present paper is to put focus on a more general design challenge; what is referred to within the present paper as the 'badly behaved problem type'. A badly behaved problem property may be realised for a large number of dynamic systems and is best explained at this stage with an example:

Consider a hypothetical and relatively slender TLP structure supporting a large and relatively impenetrable topside structure. It has been shown conclusively that the 100 year wave crest has a small margin against impacting with the topside and is shown to give relatively low loads in the tethers and the TLP. The application of the hundred year load with the appropriate safety factors poses no structural difficulties. The TLP structure will not sustain damage in the 100 year condition.

At a marginally larger return period, however, the wave crest will impact with the topside transferring loads to the structure which are very much larger than the 100 year load even including the safety factors in the 100 year load. In the worst scenario, the TLP may capsize either due to tether overloading or accidental tether disconnection due to excessive tether slack.

Whereas an annual probability of damage to the structure of 1/100 is usually acceptable, the annual probability of loss of the production unit, loss of life or major economic or environmental impact should clearly be much lower than this (1/10000 in the Norwegian sector). For a relatively smooth load mechanism, the safety factors used on the 100 year loads will usually ensure that that there are sufficient margins against collapse of the unit. For *badly behaved* load mechanisms like in the example above, the design needs to be able to capture the very rare events which are governing by focusing also on significantly larger waves than the 100 year waves.

In addition to the *probability* of serious damage discussed above, the badly behaved load mechanism will be unstable with respect to the *accuracy* of the environmental and hydrodynamic modelling. If the environmental conditions or the crest height associated with the 100 year load are marginally underestimated, the resulting 100 year tether loads will be very much larger than the calculated loads. The safety factors which are intended to capture these uncertainties will not be appropriate and a second accidental design check at a lower probability level will again be necessary.

Overview of the paper

Whereas the comparison between Snorre A model test and analysis results was the focus of a previous paper /5/, the focus of the present paper is the badly behaved problem type and on how to ensure that such a property is captured by model tests. Although the badly behaved problem type is not a TLP specific problem, the focus here is on TLP tether loading. The recent Snorre A work is used to illustrate the ideas. Finally, some recent results using an improved Volume of Fluids (iVOF) solver are presented. Badly behaved problems are by nature extremely difficult to capture using traditional analysis methods and the VOF method may be one way to capture these effects numerically.

TLP Tether Loading Mechanism

For a TLP, the single most critical structural component is the tether. Failure of the tether system may lead to loss of hydrostatic stability followed by a capsizing of the production unit.

Tether loads must be kept within acceptable limits both with respect to maximum tether loading and associated overloading of the tethers, but also with respect to minimum tether loading since slack in tethers may be as critical as tether overloading.

The total load level in the tethers is the sum of several components:

1. **Pretension at the mean sea level**

   The principle of the TLP is that mass is significantly lower than the displacement yielding significant static loads in the anchor system. This pretension ensures that the motion in the vertical directions is very small, limits the offset and setdown and ensures a positive tension in the tethers.

2. **Tide and weather dependent pseudo-static tether loads**

   With varying tidal levels, current, waves and wind the tethers will experience a variation in the pretension with time scales ranging from minutes to days. These tether loads include loads which affect all tethers equally and also overturning moment loads which yield different response in the tethers: A positive tide increases the pretension in all tethers whereas wind from the NW yields increased pretension in the NW and reduced pretension in the SE.

3. **Weather dependent dynamic tether loads.**

   The largest part of the variable tether loading stems from dynamic tether loading due to weather with time scales ranging from a few seconds to a few minutes. The dynamic tether loading includes loads incurred due to the wave and wind induced slow motion of the TLP in surge, sway and yaw (least important) via the (very important) direct response to storm wave loading to the (relatively important) impulse or ringing (or springing) loading which yields rapid tether tension oscillations close to the natural period in heave, roll and pitch. The interdependency of these effects and their complex dependence on TLP- and weather- properties, make the accurate prediction of these loads a formidable challenge.

4. **Loads due to the operation of the production unit**

   The tethers also respond to the day to day operation of the TLP. As the total pretension is the difference between the displacement and the TLP mass, the pretension will reduce when mass is brought on board the TLP. But also the horizontal shift of masses (and thus a shift in the horizontal centre of gravity) on the production unit, will affect the tether pretension: moving the derrick towards the N, for example, will lead to a reduction in tension in the N tethers and an equal increase in tether tension in the S tethers.

In order to determine the updated operational margin of the platform (point 4 above) it is absolutely necessary to determine both the maximum and minimum permitted total load levels in the tethers and also the load levels which must be kept in reserve in the event of adverse weather. Here we will not consider the resulting operational margin - the focus in the following is on setting maximum and minimum load levels due to adverse weather (point 2 and 3 above).

Limit State Control and Badly Behaved Problems

Limit State Control

According to Norwegian Rules and Regulations see e.g. [1] and [2], an offshore structure is to be controlled against overload failures at two levels; Ultimate Limit State control (ULS) and Accidental Limit State control (ALS).

In the **ULS** control, it must be shown that the structure can sustain the 100 year load level without damage. In the context of TLP tethers, the ULS control must be carried out for 100 year excursions both above and below the tether pretension level. The ULS control is assumed to be satisfied if the characteristic load multiplied by a load factor is smaller than the characteristic capacity divided by a material factor.

According to [1] and [2], the ULS control is to be checked for two formulations:

i) ULS-a: Safety factors larger than 1 is used for the permanent and functional loads, while a load factor less than 1 is used for the characteristic environmental loads

ii) ULS-b: Permanent and functional loads are now used with a safety factor equal to 1, while the characteristic environmental load is multiplied by a load factor larger than 1.

For the problem considered in this paper, ULS-b will be governing and we will concentrate on this ultimate limit state in the following.

The **ALS** control is primarily introduced for accidental loads like ship collision and loads from fires and explosions. In these controls the loads should have an annual exceedance probability of 10^{-4}. The material factor in the ALS control is often set equal to 1.0, but the characteristic capacity can be taken as the capacity corresponding to structural failure such that system effects and non-linear structural properties are utilized. This implies that local damage is permissible in connection with the ALS control, but that the overall integrity should not be put at risk.

As the example in the introduction has illustrated, excessive environmental loads could be just as dangerous as traditional accidental loads and the rules and regulations on the Norwegian sector therefore require that the ALS control is to be enforced also for environmental loads. In this connection the characteristic environmental load effect should correspond to an annual exceedance probability of 10^{-4}, while the load factor is set to 1.0.

In addition to the limit states above, the Serviceability Limit State (SLS) condition concerns the structure's ability to be operated in a practical and efficient manner whereas the Fatigue Limit State (FLS) concerns the structure's resistance to fatigue damage. In practical design work these will also have to be considered, but the present focus is on the overload limit states ULS and ALS.

Treatment of Badly Behaved Problems in Limit State Control

For the ULS control, the characteristic environmental load effect, x_c, is defined as the load effect corresponding to an annual exceedance probability of 10^{-2}. The characteristic capacity, y_c, is taken as a lower percentile (often 5%) of the distribution of the elastic component capacity. Uncertainties of various origins will be associated with both x_c and y_c and in order to ensure a sufficient margin against structural failure, partial safety factors, γ_f and γ_m, are introduced, i.e. the ULS control reads (when neglecting permanent and functional loads for illustration purposes):

$$\gamma_f \; x_c \leq \frac{y_c}{\gamma_m} \qquad (1)$$

For the ULS –b control, $\gamma_f = 1.3$ and $\gamma_m = 1.15$ will in most cases have to be used. In the context of TLP tether analysis, the load factors are applied on the tether load since the complexity of tether response offers no meaningful way to apply load factors directly on the environmental load.

Provided gross errors are avoided by an adequate quality assurance procedure, the distribution function reflecting the uncertainties in the capacity is typically well behaved, i.e. y_c/γ_m is expected to be a robust estimate of the design capacity. For offshore structures, the nature of the load side of the problem is very different. With a very low annual probability, the structure can face loads significantly larger than the characteristic load.

The values given above for γ_f and γ_m are meant to account for the typical levels of variability associated with x_c and y_c. Provided that the distribution of the annual largest load is well behaved in the upper tail, i.e. there is no dramatic shift in the shape of the distribution tail for annual exceedance probabilities in the range 10^{-2} – 10^{-4}, the design will be governed by the ULS control. This means that if the structure fulfils Eq.(1), the annual probability of structural failure is sufficiently small.

If, however, the underlying load mechanism worsens abruptly for an annual exceedance probability between 10^{-2} and 10^{-4}, fulfilling the ULS control may not lead to a sufficiently low failure probability. Such an abrupt shift is illustrated in Figure 3. It is seen that for the well behaved system (subscript wbp), $\gamma_f x_c$ will give a design load level corresponding to an annual exceedance probability typically lower than 10^{-4}. For the badly behaved problem (subscript bbp), however, it is seen that that is far from the case. The product, $\gamma_f x_c$, corresponds to an annual exceedance probability significantly larger than the accidental level of 10^{-4}.

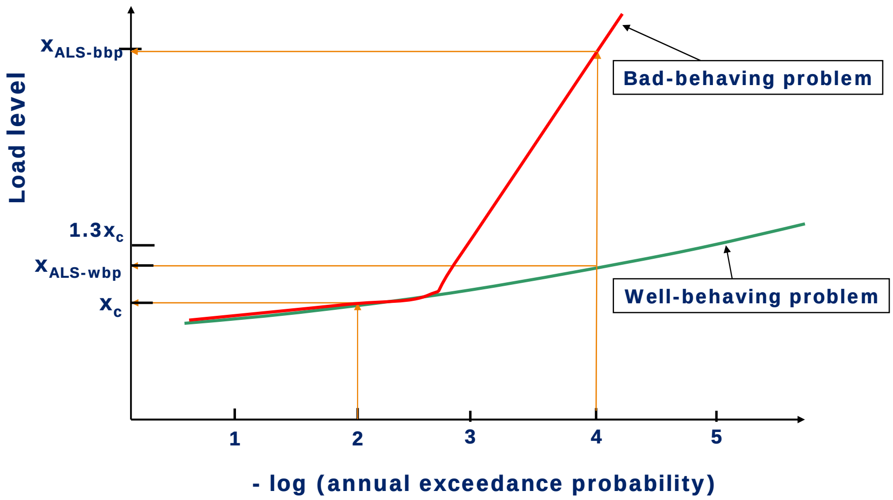


Figure 3 Illustration of the adequacy of the ULS-b control for a well behaving and bad behaving load mechanism

In order to ensure that such cases are not slipping through the design unnoticed, the ALS limit state should be applied to environmental loads. The limit state formulation is given by Eq. (1), but usually γ_f and γ_m are both set equal to 1.0.

A new structure should not be associated with such a badly behaving process for annual probability levels larger than 10^{-4}. For old structures where the load pattern for some reason is considerably changed (worsened wave conditions, reservoir subsidence, etc), one can very well foresee that a badly behaved property is realised.

Tether Slack and the Snorre A

The Snorre A was initially designed to avoid slack in the tethers in the ULS condition. The governing ULS condition requires that load factors should be applied to the dynamic tension amplitudes in the tethers. A result of this design philosophy is that it is implicitly assumed that the tether system will be damaged if tether slack occurs.

During the installation of the Vigdis module in 1996 this philosophy was abandoned and replaced with a practical requirement that the tethers should not be slack during the unfactored 100 year return event (referred to as an SLS condition). The same SLS limit was adopted in connection with the design of the Heidrun TLP which was installed at Haltenbanken in 1995.

This SLS limit is not a formal requirement, but a practical limit adopted in order to increase the payload capacity. It is important to note that the factored ULS minimum tension is still a required design case, but now against a slack event and not the zero tension event. As result of this, it is necessary to analyse tether response below zero tension and show that the governing slack event does not damage the tether system or other components.

During slack, the dynamics of the event is driven by the fact that at the time where the bottom tension is zero, the velocity of the lower part of the tether (and the anchor latch) is zero whereas the upper part of the tether (and the TLP) has a downwards motion. If the bottom tether mass is small or the velocities are gentle, the anchor latch will move downwards, keeping the top tension equal to the submerged weight of the system. But if the anchor latch mass is large or the velocities are great, the force required to accelerate the lower part of the tether assembly downwards may be great enough to cause compressive forces to propagate up the tether which may yield lift in the top tie-off assembly if the tether body can sustain the compression.

For the Snorre A tether system (Figure 4) it is necessary to be very careful when evaluating the tolerance to tether slack. The system was designed to be tensioned at all times so the possibility of slack has not been a consideration in the original choice of components. To re-evaluate an existing design for a fundamentally different functionality is always dangerous. During the present study, a very small slack (approximately 70 mm) has been introduced as the safe ULS and ALS limit since this is the slack level which may be shown to retain the basic properties of the system (the flex joints remain pretensioned, the anchor latch remain in contact with the supports et c.).

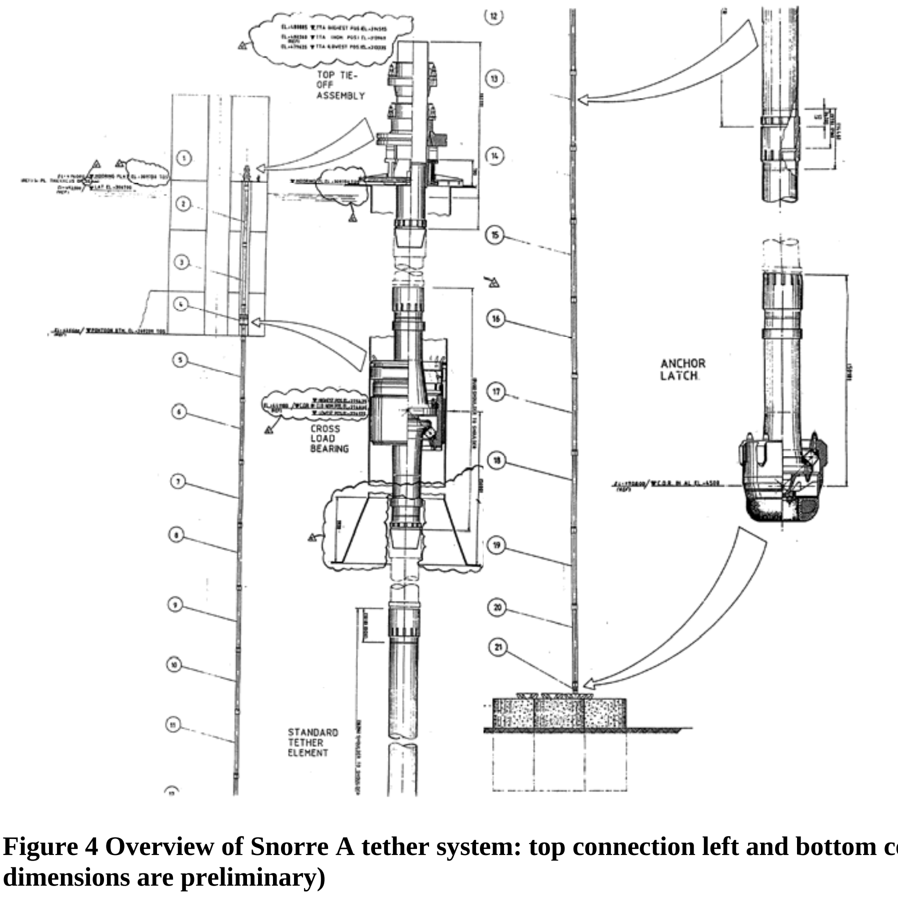


Figure 4 Overview of Snorre A tether system: top connection left and bottom connection right (note that dimensions are preliminary)

Increasing the allowable slack beyond this very small level may be possible, but it will be significantly and progressively more difficult to show that a larger slack is safe and will not damage the tether system or threaten the TLP integrity. It is, however, important to stress that slack can occur and that the Snorre A as it stands today has ULS and ALS design checks where the minimum tether loads incur slack.

Estimation of Long Term Response Extrema

It is important to note that according to Norwegian Rules and Regulations, the target annual exceedance probability refer to the load effect and not the environmental condition. This implies that in connection with the ULS and ALS control of the tethers, one should obtain reliable estimates for the tether load corresponding to an annual exceedance probability of 10^{-2} and 10^{-4} respectively.

When predicting loads corresponding to a prescribed annual exceedance probability of q, some sort of a long term analysis is required. Denoting the slowly varying meteorological characteristics (e.g. mean wind speed, significant wave height, spectral peak period, weather direction and water level) by $\vec{P}$ and the 3-hour extreme (maximum or minimum) tether load X_{3h}, the long term distribution reads:

$$F_{X_{3h}}(x) = \iint..\int F_{X_{3h}|\vec{P}}(x|\vec{p})\, f_{\vec{P}}(\vec{p})\, d\vec{p} \tag{2}$$

Where $f_{\vec{P}}(\vec{p})$ is the long term joint distribution of the involved metocean characteristics and $F_{X_{3h}|\vec{P}}(x\,|\,\vec{p})$ is the conditional distribution function of the 3-hour extreme value given the metocean characteristics. The most challenging part of Eq. (2) is the conditional distribution of X_{3h} which in principle needs to be known for a wide combination of the involved metocean and operational characteristics. For a problem like the tether extreme value problem, a large number of model tests will be required for a large number of combinations of the characteristics. This is not very attractive from a practical point of view and realistic simplifications are required.

Since extreme conditions are the present focus and the dynamic tether load due to wave excitation is dominating, the significant wave height, H_s, and spectral peak period, T_p, are selected as the primary characteristics. For the other parameters, conservative fixed values will be adopted. Table 2 shows the overload design cases with which the present paper is concerned together with the simplification of the environmental variables. Collinear waves, wind and current are tested in both head and quartering seas and the most onerous direction is taken as governing. These simplifications which are commonly employed (see e.g. /1/), are believed to result in slightly conservative extreme tether loads.

Tether Load Case	*Waves*	*Wind*	*Current*	*Tide*
ULS Minimum	100 year Hs(Tp) Contour	100 year	With and Without 10 year Current	Lowest Astronomical Tide (LAT)
ULS Maximum	100 year Hs(Tp) Contour	100 year	With and Without 10 year Current	Highest Astronomical Tide (HAT) + 100 year Storm Surge
ALS Minimum	10 000 year Hs(Tp) Contour	100 year	With and Without 10 year Current	Mean Sea level
ALS Maximum	10 000 year Hs(Tp) Contour	100 year	With and Without 10 year Current	Mean Sea level + 10 000 year Storm Surge

Table 2 Simplifying the Long Term Distribution of Environmental Loads

With these simplifications, Eq. (2) reduces to a double integral over H_s and T_p. As a consequence of this, the conditional distribution of X_{3h} is needed merely for a number of combinations of H_s and T_p given fixed values for the remaining characteristics. However, for a complex problem like the tether extreme load problem, where additionally there is some concern that rare wave deck impacts may have to be accounted for, a further simplification is preferable: the environmental contour line approach.

The environmental contour line approach aims at predicting reasonable estimates for long term extrema using short term analysis (it excludes the integration suggested by Eq. (2)). It furthermore suggests that a relatively modest number of short term sea states need to be included. More information on this approach is given in ref. [3] and [6]. At present we will merely summarize the basic steps of the method.

Using the environmental contour line approach, a reasonable estimate for the n-year value (the value corresponding to an annual exceedance probability of 1/n) can be obtained by the following steps:

1. Establish the n-year contour or surface for the involved metocean characteristics, e.g. significant wave height and spectral peak period.
2. Identify the most unfavourable metocean condition for the platform response along the n-year contour/surface.
3. Establish the distribution function for the 3-hour extreme response for the most unfavourable metocean condition along the contour line. It is important to ensure that the behaviour in the tail of this distribution is captured accurately.
4. An estimate for the n-year response value is now obtained by the α-quantile of this extreme value distribution. If, say, two metocean characteristics are included, e.g. significant wave height and spectral peak period, an adequate value of α will typically be around 0.90 for the 100 year response .

It is to be stressed that this is an approximate method, a full long term analysis, Eq. (2), is required if the estimate is to be verified. Experience with the method seems to suggest that it is relatively robust for most structural problems and that the 90% fractile is reasonable both for 100 year and 10 000 year return periods (in principle the 10 00 year load should have a slightly larger fractile than the 100 year load).

From Eq. (2) it is seen that two essentially different sources of inherent randomness is included in a full long term analysis:

- The variability related to the environmental conditions (long term variability)
- The variability of the 3-hour extreme value of the platform response given the environment (short term variability)

The basic idea by the environmental contour line approach is that the relative importance of the two sources is similar for most structural problems with the long term variability as the dominating source. Moderate changes in the relative importance can be compensated for by varying α (see step 4 above) around 0.90.

Environmental contour lines for the Snorre field are shown in Figure 5. The seastates along the 100 year and 10 000 year contours which were selected for model testing at Marin, are also indicated.

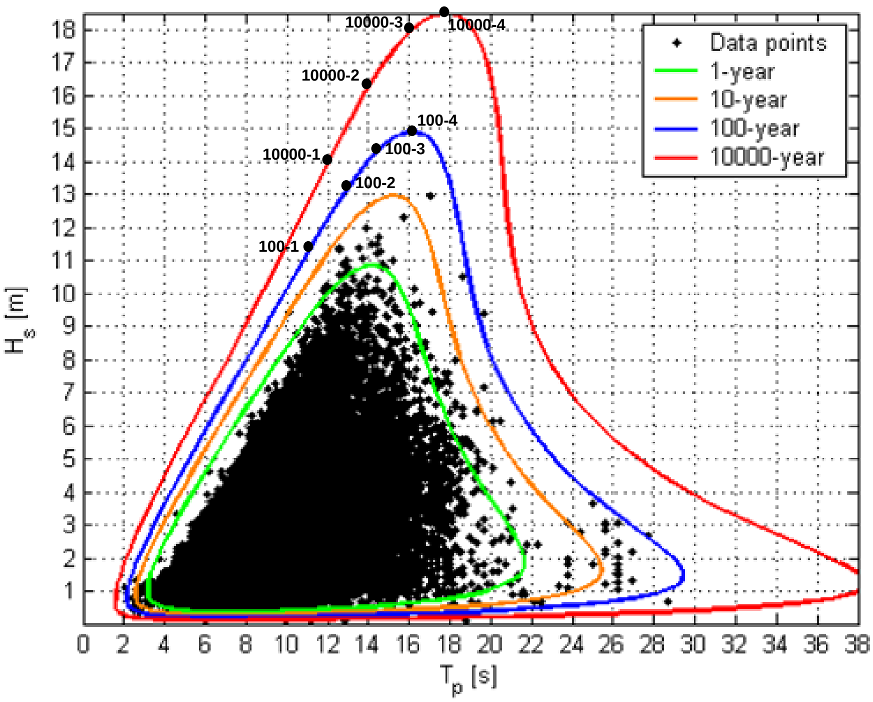


Figure 5 Contours of Significant Wave Height and Spectral Peak Period for the Snorre Field (From Ref./4/)

Other environmental conditions for the Tampen area are provided in Ref./4/, A brief summary is included below:

- The 100 year and 10 000 year sea state contours are shown in Figure 2. The selected seas are characterized by Torsethaugen wave spectra [7].
- The 100 year reference wind is 40 ms^{-1}. The Frøya wind spectrum [1] is adopted.
- 10 year surface current is steady at 1.2 ms^{-1}
- The highest and lowest astronomical tide is ±1.0 m and the 100 year (ULS) and 10 000 year (ALS) storm surge levels are, respectively, 0.9 m and 1.1 m.

Hydrodynamic Model Testing

Objective

Due to the complexity of the environmental excitation on the TLP and the resulting tether response, the accurate evaluation of tether loading in harsh environments requires model testing. The main issues which the present model tests can help clarify are:

1. Offset and slowly varying motions of the TLP in surge sway and yaw. Drift forces associated with steep waves, current and wind contribute to this effect and the response of the TLP is affected by tether pretension, added mass and damping of the TLP, tethers and risers.

   The effect of offset and slowly varying motions is important for riser design. The effect on the tether tension, however, is slight and the present study has not focused on these effects beyond ensuring that they are relatively accurately modelled in the basin. This is important because the setdown associated with large offsets may yield indirect tether loads since large setdown increases the probability of wave impact with the topside.

2. The direct response to waves (wave frequency loading) is important in the period range between approximately 5 s and 20 s and is responsible for the bulk of the loading on offshore structures. Structural loading on tethers and TLP, airgap and accelerations are all controlled by this response type which also give the largest fatigue damage to all parts of the structure.

   Linear analysis models usually represent this load type relatively accurately but have clear limitations. In the context of tether loading, it is notoriously difficult to model the extreme maximum and minimum wave frequency tether loading accurately since the extreme positive and negative excursion from the mean tension does not have the same magnitude. A basic feature of linear theory is that these excursions are equal since linear theory has zero skewness.

3. The basic idea of a TLP structure is that the natural periods in heave, roll and pitch should be kept low enough to avoid direct excitation by the waves, typically 2-3 s. With a very stiff degree of freedom with a low natural period and very small motion, damping will also be low so that any excitation may yield a large response which decays slowly. In the context of extreme tether loading, excitation of the stiff modes may be though of as impulse loading akin to the ringing of a bell and is associated either with steep waves interacting with the columns or with waves impacting on the topside[2].

   The modelling of extreme response near the natural periods in heave, roll and pitch is extremely difficult to model numerically since it is controlled by the shape and kinematics in the crest region of very large waves. Model tests are generally accepted to give a good account of these effects although it sets stringent requirements to the quality of the environmental, TLP and tether modelling.

It is also important to be clear on the effects which the present model tests cannot help resolve:

- Modifications to the topside are not model tested in the wave basin. The impact of variations in the mass distribution is handled by static calculations and the wind modelling is too coarse to capture such effects. Only parts of the topside which are subjected to large direct wave loading could conceivably influence the tether load significantly by altering the high frequency TLP response.
- The present model test does not seek to measure green sea or spray loads on exposed equipment. This can be done with reasonable accuracy, but has not been carried out.
- Risers are modelled in order to give a representation of the effect of the risers on TLP motion. The present model test cannot be employed to study accurately riser dynamics but is useful in giving the motions of the TLP as input to a numerical analysis of riser response.

[2] In addition to this ringing phenomenon, one will also experience a sustained second order response in this period band which is commonly referred to as springing. This response process is mainly of concern for fatigue, but occasionally it is difficult to separate between a ringing event and a strong springing episode.

Model Test Philosophy

As discussed above, the distribution of tether loads which is a function of the long term distribution of waves, wind, water level, current and the weigh distribution of the TLP, has been simplified to the analysis of waves along the 100 year and 10 000 year contour curve (Figure 5) for two directions of environment incidence. W indicates waves, wind and current propagating towards the living quarter (from the West) whereas NW indicates quartering seas incident from North West.

The first step in the model testing programme is therefore to identify the governing seastate for each of the four responses of interest (Table 2) by running typically four three hour realisations for each of the seastates and both directions. This activity indicated that seastate 100-4 and 10000-4 from NW were governing for minimum tension (which give the possibility of tether slack) in the ULS and ALS conditions respectively. The minimum tension occurs in the downwave SE cluster of tethers. Seastate 100-2 and 10000-2 from NW give the governing maximum tension (which give the possibility of tether overload) in the NW cluster of tethers.

Although the use of contour lines simplifies the analysis considerably, the requirement that the 90% fractile of the three hour extreme value distribution must be used to estimate the 100 year and 10000 year responses implies that a significant number of realisations of the governing seastates need to be run. The 90% fractile implies that the design value has a10% chance of being exceeded in three hours such that the design value can be expected to be exceeded once every 10 three hour simulations. Particularly if the response if of a badly behaving nature, it is clear that a large number of realisations of the governing seastate needs to be run in order to obtain a reliable estimate of the design value since the response level at lower probabilities cannot be extrapolated to the design level.

The second step in the model testing programme is therefore to concentrate on the governing seastates and run a sufficient number of realisations to estimate the design value. The number of realisations should be decided *a priori* based on the initial screening runs in order to avoid the bias in the distribution which would be present if the testing was terminated on the basis of observations.

Execution

Model tests were carried out at a scale of 1:62.5 at the facilities of MARIN in Wageningen in The Netherlands. These facilities offer the opportunity to test accurately a wide variety of seastates, water depths and wind and current fields.

The TLP hull was manufactured in PVC with stiffeners in the transition between the columns and pontoons. Tether conduits were modelled as closed vertical pipes underneath the centre of each column ensuring that the rotation point of the tethers is correctly modelled.

In order to obtain a very stiff hull structure, the top of the columns were connected using a steel frame arrangement. The topside was modelled in four separate quadrants supported by 6 degrees of freedom force transducers mounted on top of each column. This arrangement offers the possibility of measuring forces on each of the topside quadrants.

In order to capture the response due to possible wave impact with deck events, the lower part of the deck was modelled accurately. A coarser representation of the upper deck structure was included in order to include a reasonable representation of the wind loading on the topside. The wind loading was provided by a bank of wind fans 5m upwave of the model which were calibrated to give the correct mean wind and gust spectrum.

Only one tether was modelled underneath each column both in the model test and in the analysis model. Tether tension reported in the following is therefore the total tension in the lumped tethers underneath each corner. Tethers were modelled using steel piping yielding a rigid system with correct submerged weight and drag. The tethers were hinged at the seabed and short springs between the top of the tethers and the TLP provided the flexibility in the tethers. Rigid risers were lumped with ten model scale risers representing 46 full scale risers. Flexible risers on the east side of the TLP are ignored in the model test and in the analysis work.

The present tether modelling approach should be used with caution in very deep water since the tether contribution to inertia is neglected in the stiff degrees of freedom (heave, roll and pitch), an effect which may be shown to be insignificant in the present water depth. There is, however, a need to evaluate how the model test (hinged-rigid-linear spring) tether system behaves relative to the full scale (flexjoint-flexible-flexjoint) tether system, particularly when the tether is close to slack.

Collinear waves, wind and current are run in two directions, incident from the W and from the NW. An overview of the number of three hour simulations run for each direction and seastate is shown in Table 3. In addition a number of seastates relevant for fatigue were run.

Seastate	***Environment from NW***	***Environment from W***
100-1	2	2
100-2	**32**	10
100-3	14	14
100-4	**65**	8
10000-1	4	2
10000-2	**14**	4
10000-3	8	10
10000-4	**27**	16

Table 3 Number of 3hr realizations in Model Test

Three hour simulations of the seastates were run with and without wind and current. The bulk of the tests, and all results reported in the following, are run with wind but without current. Current was run merely to verify that the effect on tether tension amplitudes is small for the Snorre A with its relatively small water depth and current velocity.

Tests were run with three different water levels (and thus pretension levels) as indicated in Table 2 since the draft has a significant effect on dynamic tether tension and on the probability of wave impact with the deck.

The model was extensively instrumented during testing:

- Tension at the top and bottom of the tethers and at the top of the risers
- TLP motion in 6 degrees of freedom
- Topside accelerations
- Global forces on the topside
- Breaking wave induced forces on the columns
- Relative surface elevation (airgap) at 16 positions

- Absolute surface elevation with and without the TLP present in the wave field

In the following, all results from the model test are reported with full scale values.

Figure 6 Hydrodynamic Model

Figure 7 Hydrodynamic Model, NW Governing Seastate

In order to verify the important properties of the model a number of qualification tests were carried out:

- Swing tests in air in order to verify the radii of gyration
- Restoring tests in which the offset and set-down were measured as functions of the restoring force
- Decay tests in all degrees of freedom
- Simulations with static wind alone, dynamic wind alone and current alone where relevant
- Measurements of hull bending stiffness by measuring static tether response to moving weights on the topside

The conclusion from the qualification tests and subsequent comparisons with analysis [5] is that the mechanical system is modelled accurately and that the discrepancies between the model test results and traditional analysis tools may be discussed in terms of the excitation on the system.

Model Test Results

The main conclusions from the model test are as follows:

- The governing case for tether slack is the 100 year SLS criterion. This occurs in the SE tether with weather from the NW and the largest H_s 100 year seastate (100-4). This condition is controlled by wave frequency effects, high frequency tether tension is not important.
- The governing case for tether yield is the intact 100 year ULS-b maximum load case. This occurs in the NW tether with weather from the NW and a very steep 100 year seastate (100-2). For this condition, the high frequency contribution is important since it is correlated with the wave frequency contribution.

- The elevation of the deck on the Snorre A is sufficient to avoid large horizontal wave impact with the topside. It appears, however, that vertical wave impact with the topside and (more importantly) strongly nonlinear wave interaction with the columns contribute to tether tension for the largest 10 000 year events. Nevertheless, the 10 000 year seastates do not incur the governing tether loading.
- The relatively low current velocities in the Tampen area are not important in the evaluation of tether tension.

Consider a critical seastate where several three hour realisations have been run. From each of the three hour simulations, the most critical value (in this case the largest positive and negative excursions from the mean tether tension) may be extracted. The critical values from each three hour simulation are then ordered after severity and assigned a probability, F, of non exceedance. F=0.9 thus corresponds to a value which have 10 % probability of exceedence in three hours.

If the measured value is plotted on the x-axis and –ln(-ln(F)) is plotted on the y-axis (a Gumbel plot), a curve may be drawn and a design value may be found. The target value F=0.9 has the value –ln(-ln(0.9))=2.25 in a Gumbel plot. This approach is shown in Figure 8 and Figure 9 for the governing minimum and maximum tether forces. Both the 100 year and 10 000 year seastates are shown.

The Maximum Likelihood estimates of the Gumbel parameters are shown together with the experimental data. The Gumbel assumption can handle strongly nonlinear load mechanisms, but not a badly behaved load mechanism which features a discontinuity in the loading function.

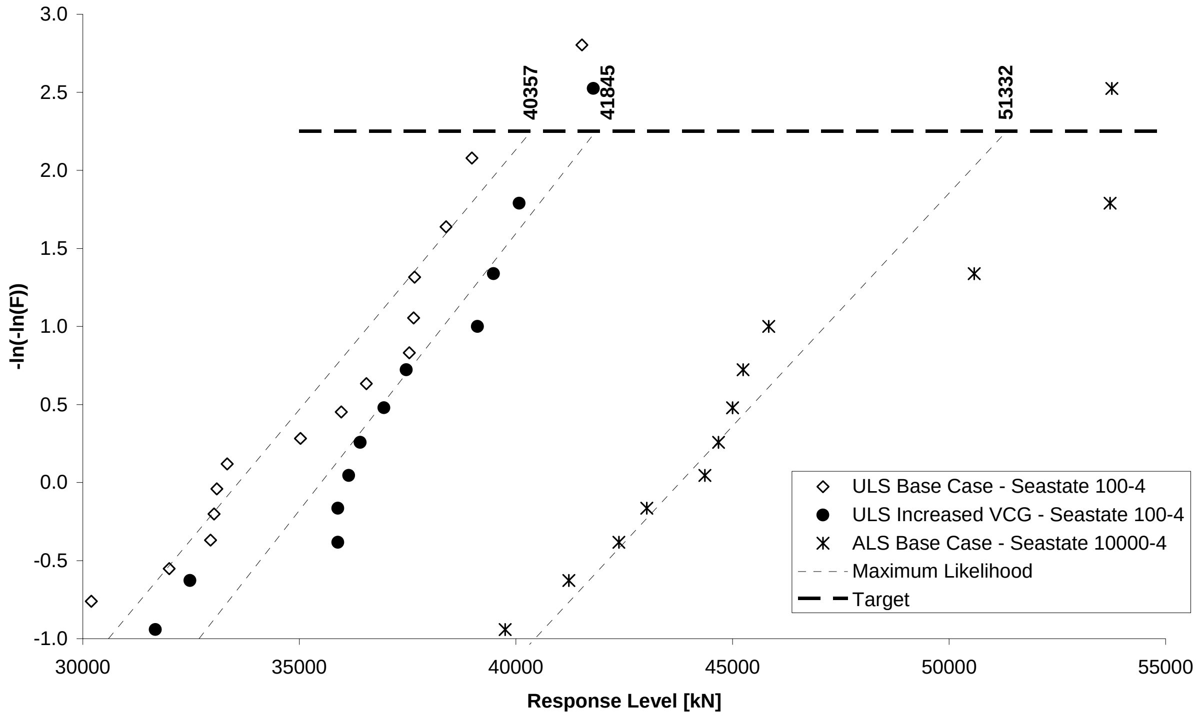


Figure 8 Measured Minimum deviations from mean tension in SE corner with all weather form NW

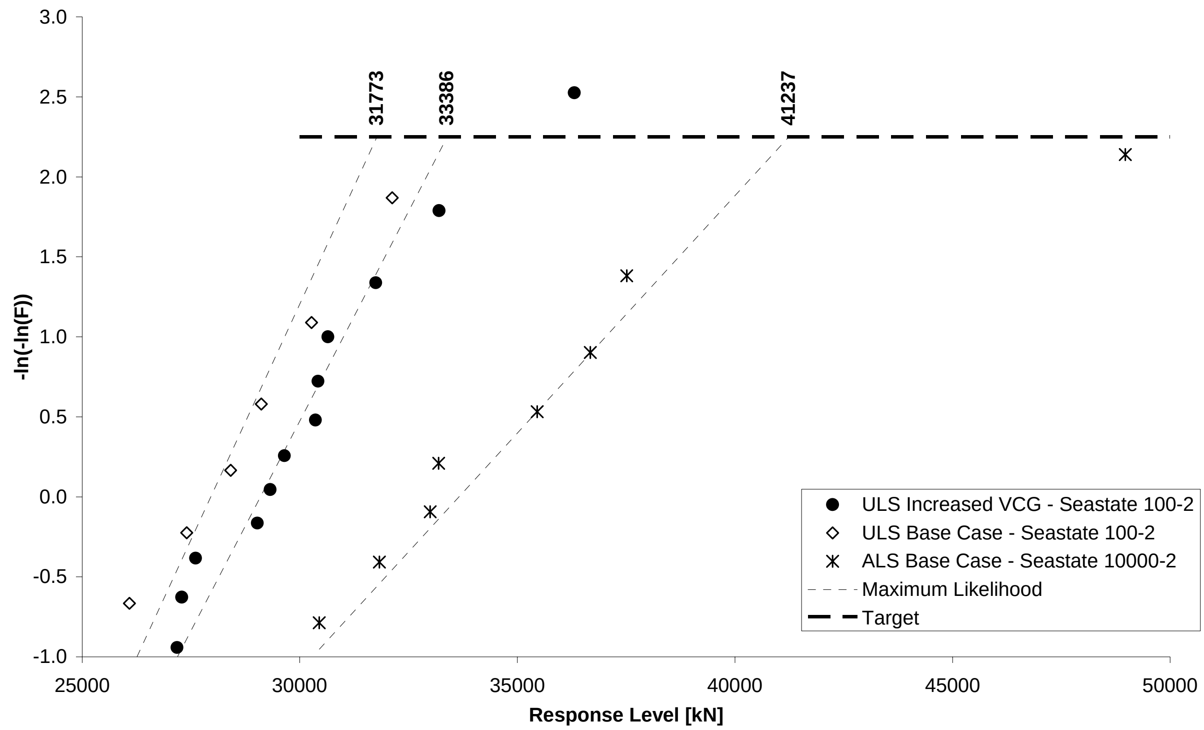


Figure 9 Measured Maximum deviations from mean tension in NW corner with all weather from NW

It is seen both from the relative smoothness and from the gradient of the curves in Figure 8 that the minimum tension amplitudes are well behaved. High frequency response, although not small, does not contribute to the extreme events since it is not in phase with the governing wave frequency minimum tension (it sets in after the minimum tension occurs). For the largest 10 000 year events, however, there is a tendency for the high frequency loading to challenge the wave frequency minimum.

The time series of the extreme negative 100 year and 10 000 year minimum tension events are shown in Figure 10 and illustrate this point. The 100 year event occurs together with a large wave trough in SE and the minimum tension is realised before the wave impacts with the columns and sets up significant high frequency response. For the 10 000 year event, the same mechanism is evident, but the high frequency response is large enough to yield the minimum tension. This may indicate that the larger scatter in Figure 8 which appears to be present for the largest 10 000 year measurements is not merely statistical variation.

The maximum tension amplitudes in Figure 9 are not as well behaved as the minimum tension level. The gradient for the 10000 year curve differs significantly from the gradient of the 100 year curve indicating a significantly more nonlinear system. In addition, the largest value measured is very large although it is difficult to conclude that a badly behaved property is realised based on a single measurement.

The time series of the largest 100 year and 10 000 year maximum tension events are shown in Figure 11. High frequency tether response is an important contribution to the total tension level in both 100 year and 10 000 year seastates but since the high frequency response is strongly nonlinear it becomes progressively more dominant at lower probability levels. The high frequency tether loading stems primarily from the interaction of steep waves with the column (ringing) and to a lesser degree vertical wave impact with the deck in the area around the columns.

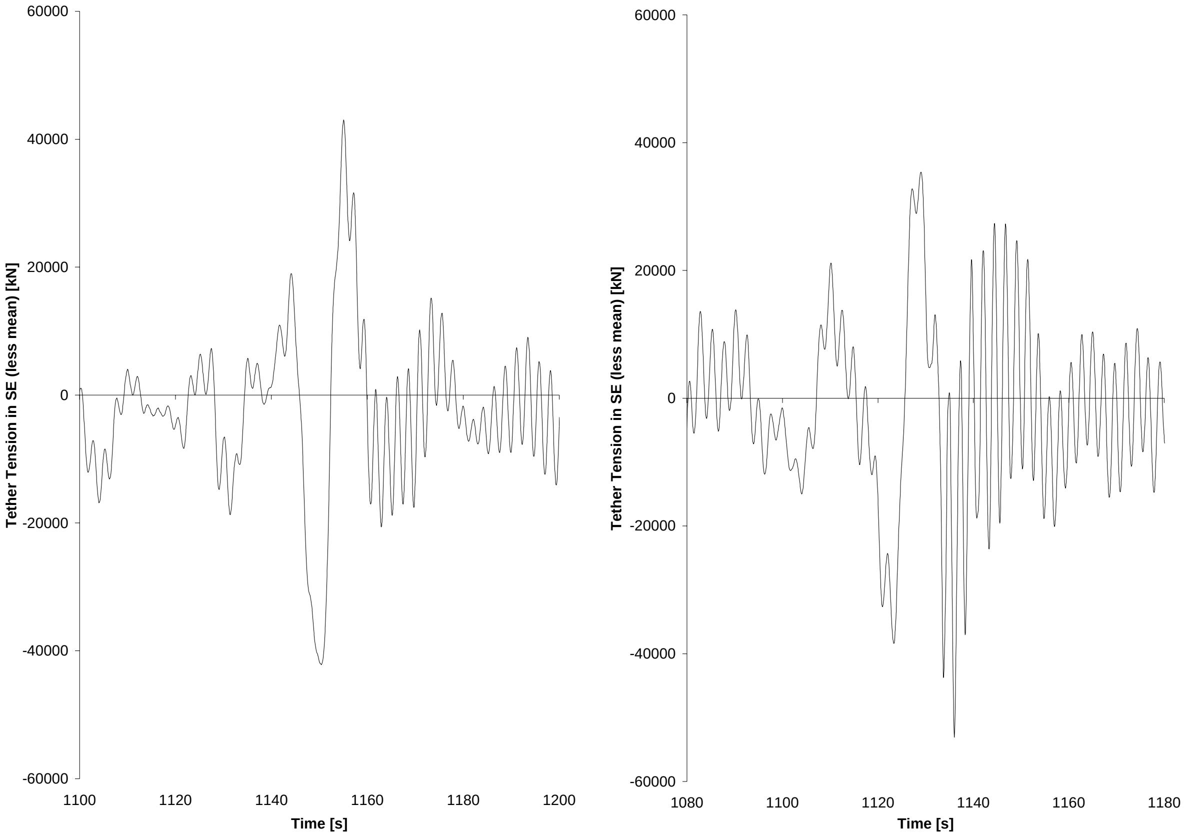


Figure 10 Governing 100 year (left) and 10 000 year (right) negative tension excursions in SE tether

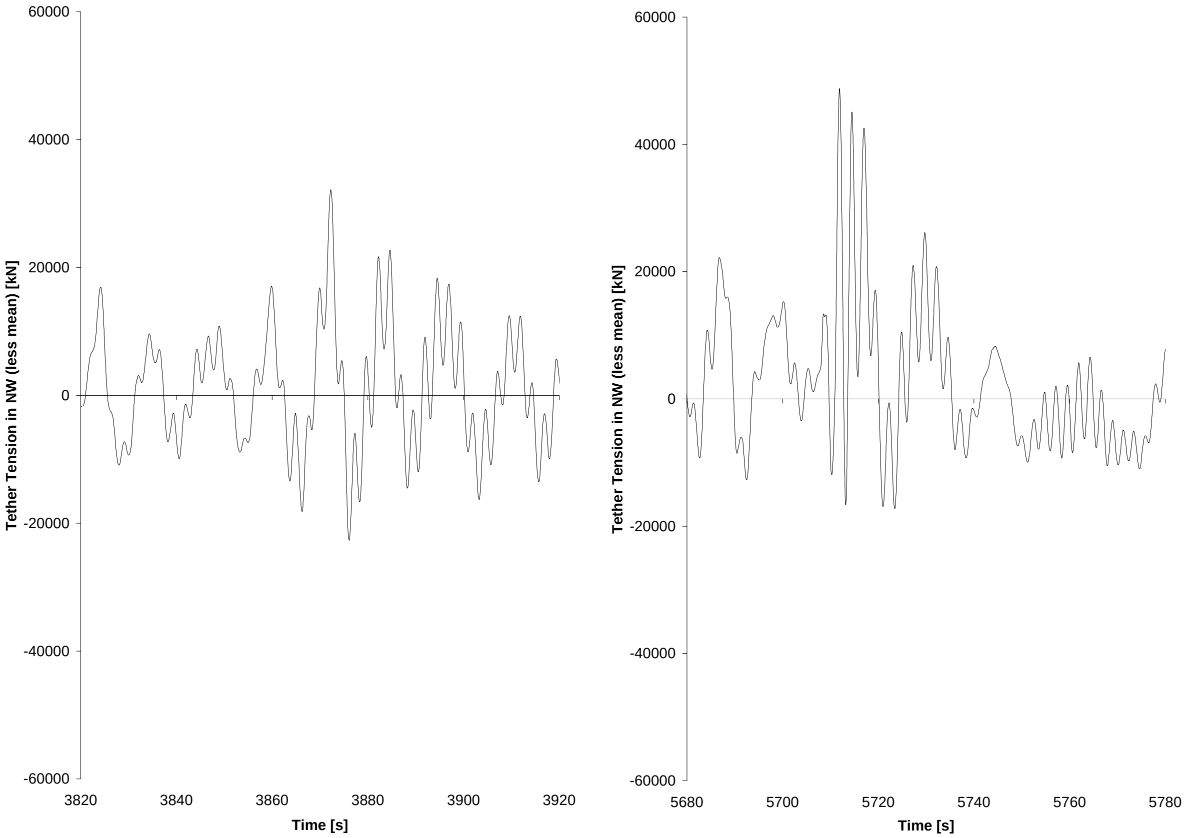


Figure 11 Governing 100 year (left) and 10 000 year (right) positive tension excursions in NW tether

Based on the initial screening measurements and measurements from the (not governing) W weather case it appears that a kink in the distribution does indeed set inn for maximum tether amplitudes close to the 90% fractile in the 10000 year condition, but that it sets in too late to be governing over the 100 year condition.

The extensive model testing programme has provided a data base of results with which to compare analysis models and study physical effects which is nearly inexhaustible. One example is shown in Figure 12 concerning a quick investigation of an extreme 10 000 year tension event with weather from the W, carried out during model testing due to a concern that a horizontal deck impact event had occurred. The time series plots included are the tether tension in the upwave and downwave tethers, the relative wave elevation, the TLP pitch motion and the output from the vertical deck loading force transducer in the NW quadrant of the topside.

- There appears to be a very large impact or ringing event which gives very large tension in the W tethers at 12025 s followed by a very small tension level in the E tether at 12027 s. A significant and slowly decaying high frequency response is set up as a result of this.
- There is a large pitch event which is initiated at 12024 s towards negative pitch (nodding towards the E). This is consistent with a horizontal deck impact event.
- There were no significant horizontal topside loads recorded. At 12025 s, however, there is a vertical impact recorded underneath the NW topside (note that inertia is not filtered out of the force transducer signal) indicating a vertical deck impact from underneath the deck. The magnitude of this loading is small, however, and not sufficient to set up the global tether response.
- Airgap probe 16, 15 and 5 are respectively 50 m W of the W pontoon centre, 3 m W of the NW column and centrally above the W pontoon. A horizontal impact event would occur when the extreme crest was between probe 16 and probe 15 at approximately 12022 s which is earlier that the observed impact event. With a still water airgap of 24.4 m, it appears from the probe 5 time trace that the available airgap is exceeded such that there is indeed a vertical deck loading.

For this case, it is concluded that a marginal exceedence of airgap occurs underneath the deck but that this does not set up the very large high frequency response. The high frequency response in the example in Figure 12 appears rather to be set up by the wave impact with the E columns as a ringing event.

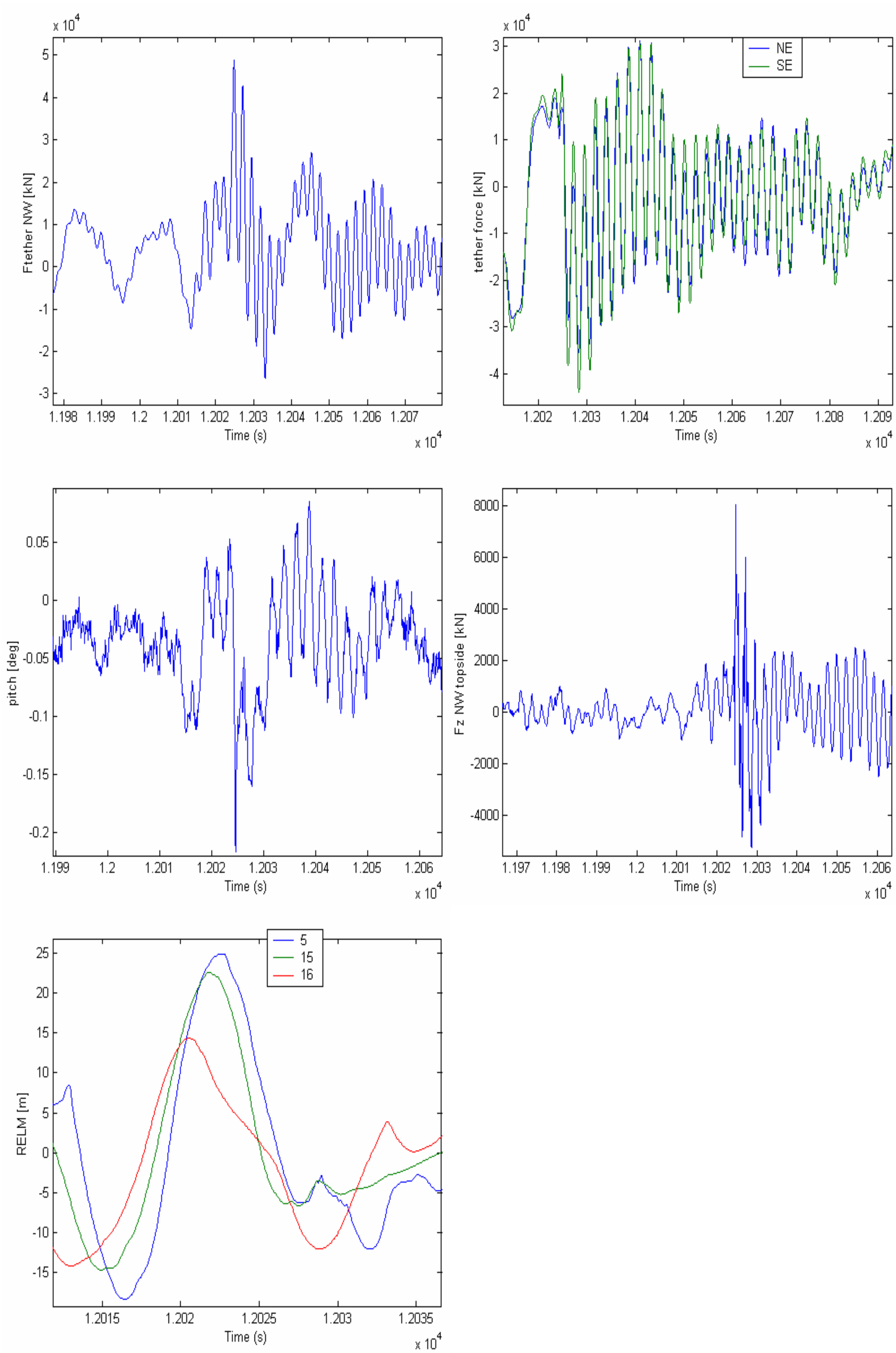


Figure 12 Measurements of Extreme Event (Seastate 10 000-4 from W)

Application of CFD to the Analysis of Badly Behaved Problems

Introduction

For linear or weakly nonlinear problems, 3D linear diffraction theory (including second order effects) provides valuable insight into the behaviour of floating offshore structures. This was even the case for the high waves in which the Snorre As was tested, as was shown in [5]. However, this type of method cannot be expected to capture the badly behaving problem type discussed previously which features a discontinuity in the loading function. An example of such a problem is the situation where the deck of a TLP is strongly hit by a wave crest. Although the Snorre A is found to be well balanced with respect to ULS and ALS load types, it is important to develop simulation methods that are able to capture the badly behaved problem type. As part of the development of such a method, the behaviour of the Snorre A was simulated using the improved Volume Of Fluid (iVOF) method.

Methodology

The improved Volume Of Fluid (iVOF) method is developed in co-operation between the University of Groningen (RuG) and MARIN. It enables the computation of the complex, non-linear free surface flow around arbitrary geometries. The fluid domain is subdivided into rectangular grid-cells which are labelled as fluid cells (open to flow) or empty cells (closed to flow) due to the presence of a solid. By means of conservation of impulse, conservation of mass and the free-surface boundary conditions, the flux through the cell boundaries and the pressure in the cell centres are computed. Recently, the method has been further extended to enable the computation of floater motion response, including the full non-linear interaction with the surrounding flow. Arbitrary external forces can be added to the equation of motion, enabling the modelling of the tether forces. More details on the iVOF method and some recent applications can be found in for example [8] and [9].

At present, it is not possible to do long simulations of irregular waves due to the large computational times. The simulations have therefore been carried out in regular waves in order to investigate at least qualitatively the effect of wave impact with the topside. In order to show the principle of the badly behaved load mechanism, simulations were carried out with 2 different wave heights:

1. Wave height of 29.7 m, wave period 13.0 seconds (Ak approx. 0.35).
2. Wave height of 36.4 m, wave period 13.0 seconds.(Ak approx. 0.43)

The tethers have been modelled as mass-less stiff axial springs. This assumption is made because the tether mass is small compared to the TLP mass (about 5.5 percent). Like in the model tests, the 4 tethers at 1 column have been lumped into 1 single tether. The analysis has been run with waves incident from the west (directly on the living quarter).

The modelled geometry of the Snorre A is shown in Figure 13. The cell size near the TLP is 2x2x2 m:

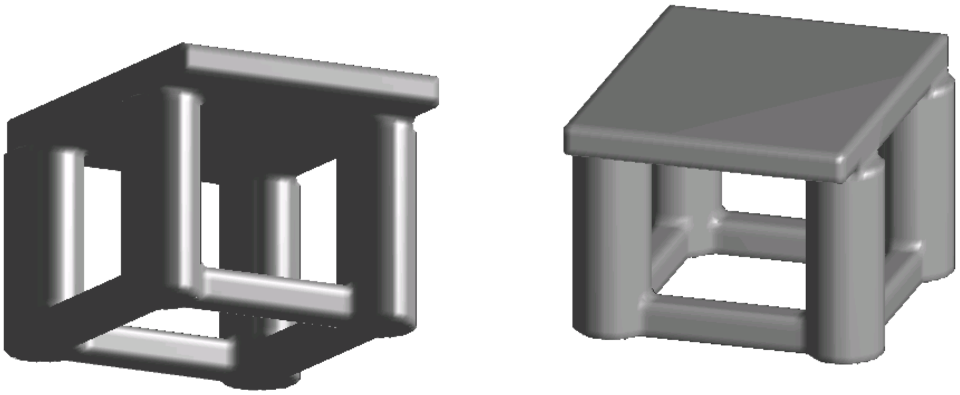


Figure 13 Snorre A Model

The simulations are initiated with the water at rest. The first wave period is used to start-up the wave orbital velocities at the inflow boundary upstream of the TLP. Stokes 5th order wave theory is used. At the downstream side of the TLP the domain is extended for about 1500 meters to avoid wave reflections from that direction to occur within the simulated period, using so-called stretched cells which exponentially expand in size in downstream direction. A 3D view of the domain is shown in Figure 14.

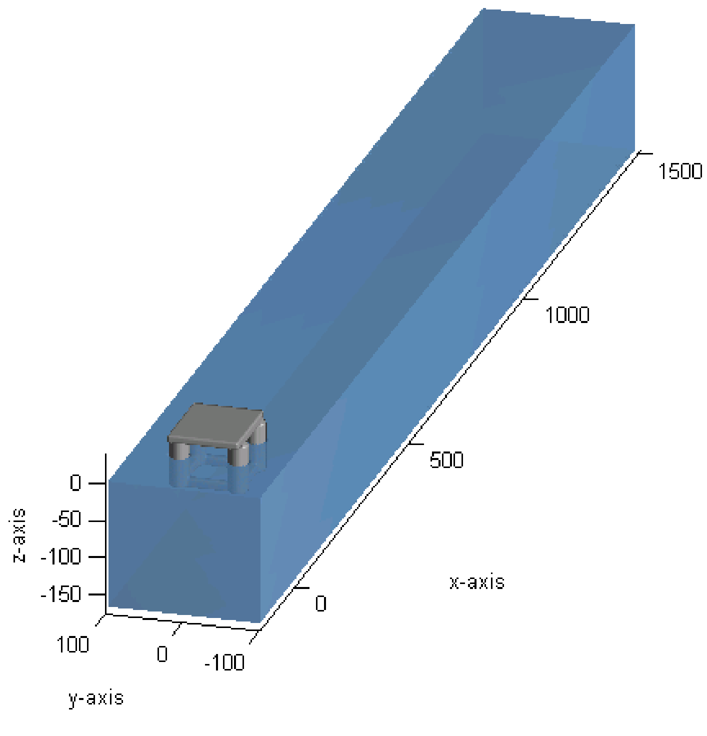


Figure 14 Double Computational Domain

In the simulations, a symmetry condition was used and the computation thus included only half the domain indicated. A total of 718,160 grid cells were used in the simulations.

Results

A total of almost 3 wave periods was simulated (36 seconds). The computational time on a modern PC was about 1 week. Prior to the 3D simulation, a 2D simulation without the TLP was carried out to check the quality of the computed undisturbed wave (similar to what is done in the model basin). The wave elevation at the centre of the TLP (H=29.7 m left, H=36.4 m right) is shown below. The non-linearity in the waves (steep crest, flattened through) can clearly be observed.

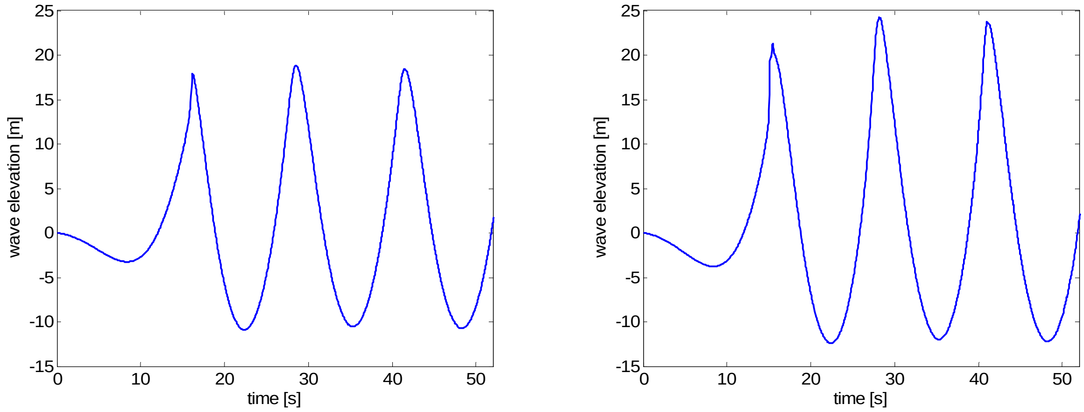
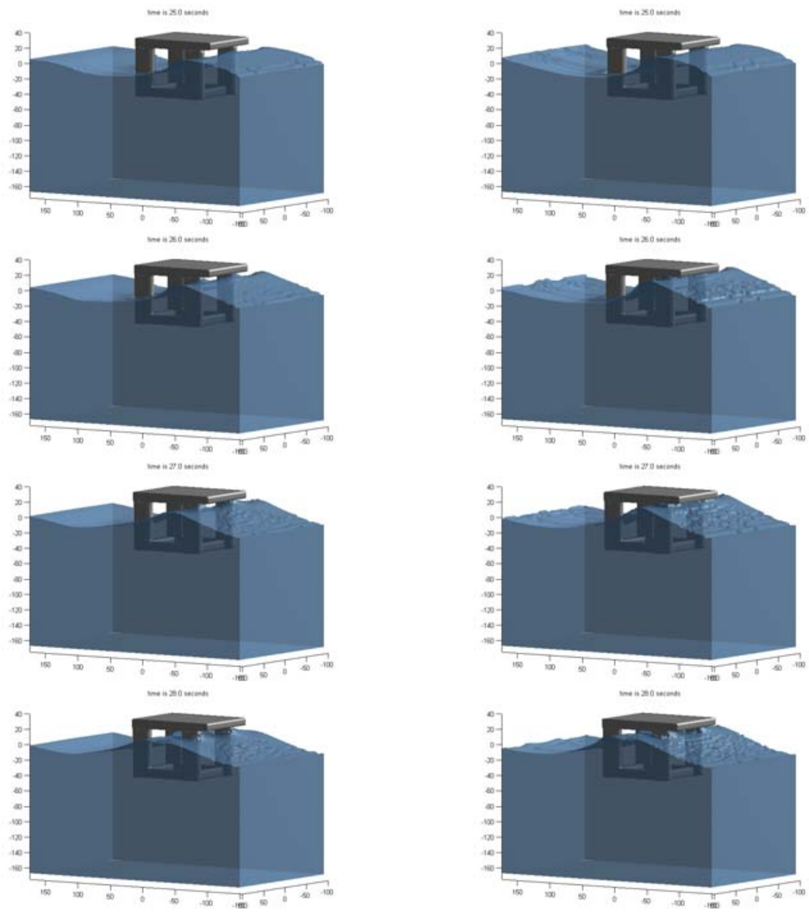


Figure 15 Incident Regular Waves

The following signals are output from the simulation:
- TLP motions in 6 degrees of freedom
- Tether forces
- Hydrodynamic forces on the TLP

Several snapshots from the simulations from T=25 s through T=31 s (smallest wave height is shown on the left and the highest wave height on the right) are shown in Figure 16:



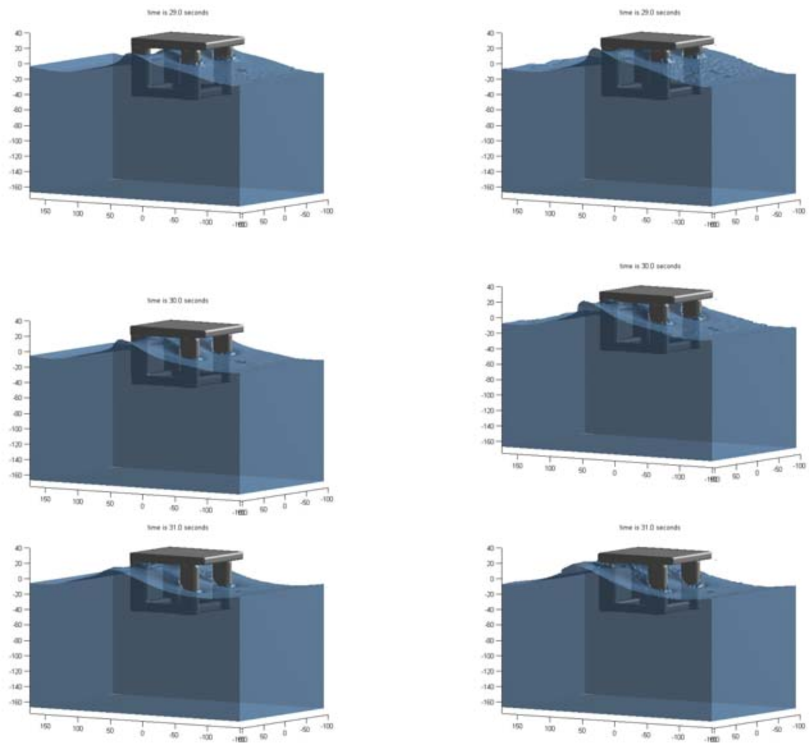


Figure 16 Snapshots during iVOF Simulation (largest wave right)

It can be seen that in the case of the lowest wave, the wave crest just misses the deck. The higher wave however causes significant vertical deck impacts. This is illustrated below where the following signals are shown:

- The top tension in the forward tethers
- The top tension in the aft tethers

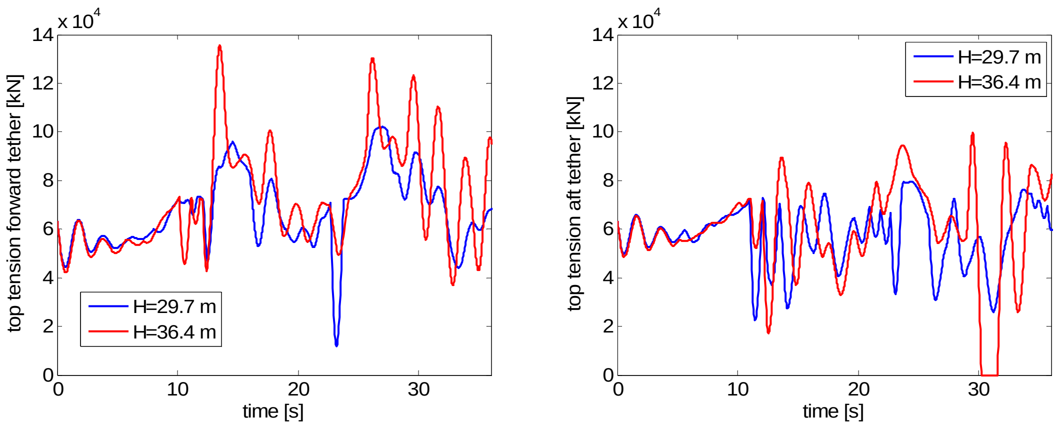


Figure 17 Tether Tension Timeseries

The tether loads clearly show the familiar, combined resonant and wave frequency response. The high-frequency, resonant variations in the tether loads are significantly larger in case of the highest wave. Furthermore, the maximum tether load is highest on the forward tether, but the aft tether becomes slack after the wave crest has passed the aft columns (T=30 s). This clearly shows the ‘badly behaved load mechanism’: A wave just missing the deck induces relatively moderate dynamic tether forces whereas a slightly higher wave that hits the deck can cause slack tethers and subsequent serious damage to the platform. Traditional methods (linear or second order diffraction theory) are not capable of predicting such effects.

Finally, the surge, heave and pitch motion of the TLP are shown in Figure 18:

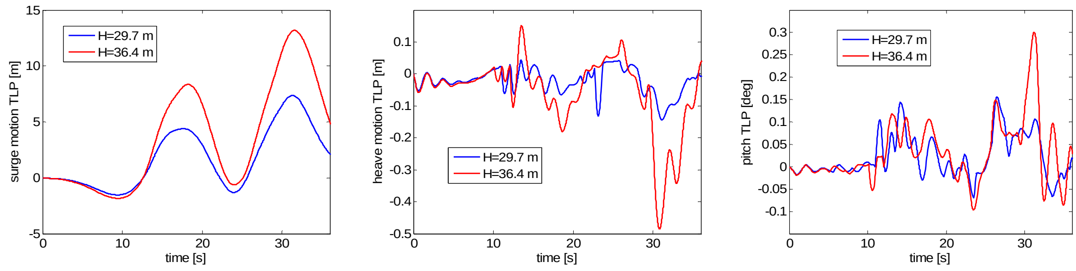


Figure 18 TLP Motion Timeseries

These show that:

1. Due to the mean wave drift force, the TLP is pushed backwards also causing a mean, non-zero setdown.
2. Heave and pitch motions are small and follow the tether tension behaviour with the typical combined wave-frequency and resonant TLP response.

Due to the fact that the TLP has not reached its mean, wave drift force induced surge offset (and setdown) yet, it is most likely that subsequent wave crests lead to higher tether loads due to a further reduced airgap. However, this appears to be an effect which is particular for regular waves since extreme waves in nature will occur as single events which are very much larger than waves in the vicinity and this effect was not investigated further.

Discussion

Response Return Periods and Badly Behaved Problems

It has been the aim of the present paper to illustrate that the badly behaved problem type is a real issue which should be accounted for in design. It has further been the aim to illustrate the inadequacy of basing the design on one or a small number of three hour realisations of the governing seastate.

The expected maximum or minimum value obtained from a single three hour simulation is significantly lower than the required design value which may yield return periods of the design value of 10 years or less. If the response is well behaved, an extrapolation of the maxima observed to a lower probability level and the use of load factors may still ensure a relatively robust design.

But if the response is of the badly behaved type, due to wave impact with the topside or other strongly nonlinear effects, the design load cannot be extrapolated from a small number of simulations since the loading function is discontinuous. It is therefore necessary both to run a sufficient number of realisations such that the likelihood of observing the design value is acceptable, and also to run a second ALS check on the environmental conditions to investigate the behaviour at a very low probability level.

The Snorre A

Based on a concern about the integrity of the Snorre A tethers and the possibility of a badly behaved response process, a large model testing programme was set up in order to investigate this. It is concluded that there may indeed be a discontinuity or a strongly nonlinear component in the loading function of the tethers but that this sets in at sufficiently low probabilities such that it is not governing for the tether integrity.

The Snorre A tethers are in fact well balanced with respect to the ULS and ALS loading as is illustrated in Figure 19. Figure 19 shows the utilisation of the tethers above (yield) and below (slack) the pretension level for the different design cases. A utilisation of 1.0 corresponds to a conservative maximum tether tension level for the ULS and ALS cases (they differ by a factor of 1.15), zero bottom tension for the SLS condition and the tension corresponding to the small allowable slack level discussed previously for the minimum ULS and ALS cases. It is seen that the ULS and SLS cases are governing for maximum and minimum tension respectively. The difference between these governing cases and unity is the margin which may be used for the operation of the platform.

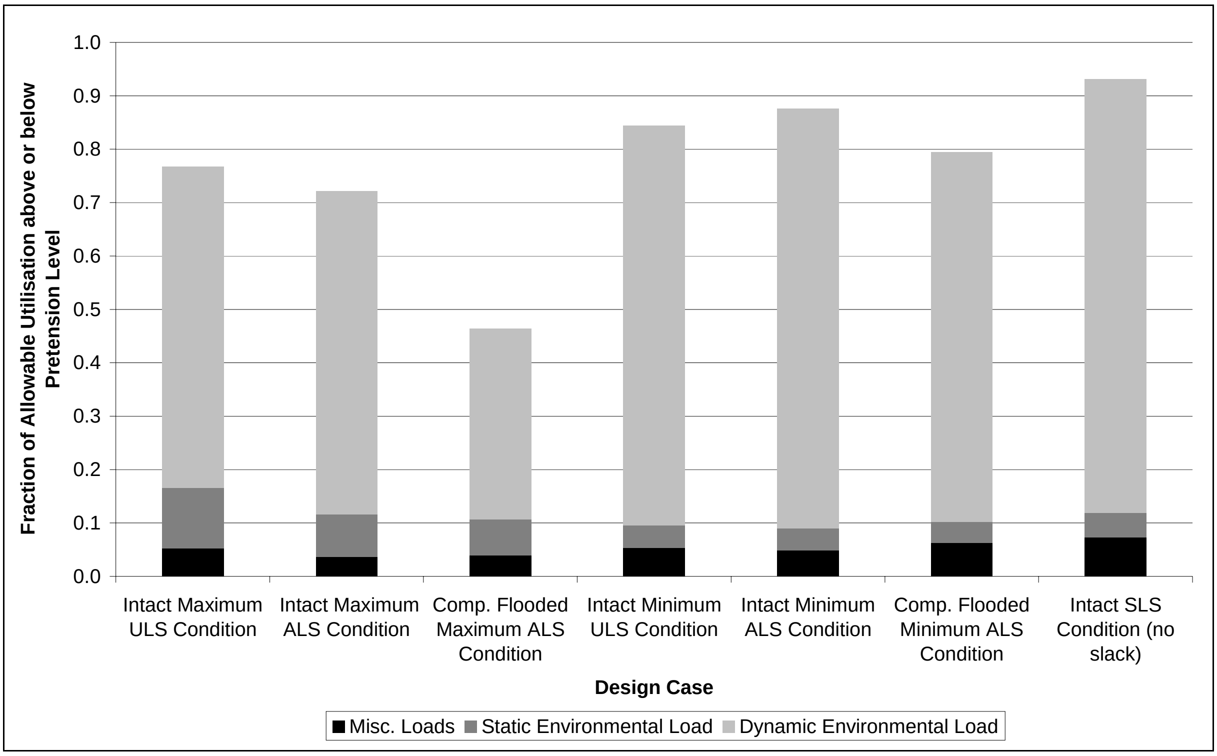


Figure 19 Tether Utilisation for the Different Design Cases

A remaining concern with the Snorre A tether integrity is the possibility that the method of modelling the tethers in the model test is not representative of the full scale system close to slack. Hinging the tethers about the seabed and representing the tether stiffness by a spring between the top of the rigid tethers and the TLP hull may have unintended effects for very low tension levels. This effect is currently being investigated.

Computational Fluid Dynamics

Stable and accurate numerical simulations of complex fluid motion problems using the iVOF solver remain a significant challenge (Ref. [8] & [9]). Nevertheless, as has been shown above, the accurate analysis of strongly nonlinear wave interaction with structures is becoming a reality for short, well defined incident wave trains.

In the present paper, however, it has been stressed that very long simulations of representative seastates are necessary in order to identify the design load level. The load level needs to be associated with a probability of occurrence in order to be meaningful in a design context. The simulation of irregular seastates over several hours using iVOF or alternative CFD methods is still below the horizon.

The main challenge before these methods may be used to determine or verify the design load and response levels is therefore to develop methods which identify short and well defined wave trains which may be used as design waves and tie the resulting response to the overall probability level. This is a formidable challenge:

- Regular waves may be used which are representative of the irregular governing waves. It is very difficult to verify that a regular wave is representative of an irregular wave and to construct a probability distribution based on representative regular waves.
- Short wave packets which contain the wave groups which are assumed to be governing may be extracted from model tests or separate numerical simulations and run through the iVOF solver. This may be a promising method coupled with a peak over threshold statistical approach.
- Transient wave groups (see e.g. /10/) which are representative of extreme waves in a seastate may be run through the iVOF solver. For a complex response system, the reconstruction of the statistics of the response may be difficult.

Acknowledgements

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