GREEN WATER FROM THE SIDE OF A WEATHERVANING FPSO

Bas Buchner
Maritime Research Institute Netherlands (MARIN)

ABSTRACT
In the paper the relative wave motions along the side of a weathervaning FPSO are investigated. In non-collinear directions of wind, waves and current the vessel does not always encounter head waves. With wave headings of typically 15-30 degrees from head waves, the strongly non-linear relative wave motions along the side can come above the freeboard of the vessel and result in greenwater flow onto the deck. At several existing FPSOs this already resulted in damage, typically at midships and further aft.

The paper first discusses the background of the occurring phenomena. Then a method for the prediction of the non-linear relative wave motions along the hull is presented. This is necessary to predict the possible freeboard exceedances. Finally a new estimation method for the prediction of the green water loads on slender structures is presented, based on the exceedance of the freeboard on the side.

INTRODUCTION
In non-collinear directions of wind, waves and current a weathervaning FPSO does not always encounter head waves. Wave headings of typically 15 to 30 degrees from head waves can occur. In this type of conditions, greenwater on the deck is not only a problem in the bow area of the FPSO [2,3], but it can also come onto the deck from the side of the ship. The typical observed phenomena are shown in Figure 1. This type of green water occurrences caused already damage on several FPSO’s, typically at midships and further aft [12]. Although the damage generally concerns smaller structures (hand rails, piping, cable trays, stare cases, etc.), this damage can still result in safety problems on board. It is also a serious problem for people working on the deck. The green water from the side should therefore be addressed in the design of FPSO’s.

The first problem to be dealt with, is the fact that the relative wave motions along the side of the hull were found to be very non-linear in model tests. The predictions with linear 3D diffraction theory underestimate the extreme relative wave motions significantly. This is probably the reason why it is not always taken into account properly in existing FPSO’s. In the paper the origin of these non-linearities will be discussed first. Then a method to take these them into account in the prediction of the occurrence of green water is presented.

The second problem is the prediction of the amount and loading due to green water from the side. This problem is addressed in the second part of the paper, applying basic hydraulic models.

This paper is partially based on the results of the Joint Industry Project ‘F(P)SO Green Water Loading’. Model test were carried out on the FPSO hull shown in Figure 2. Its main dimensions are given in Table 1. In Figure 1 the measurement channels presented in this paper are indicated. Tests were carried out in regular waves as well as in irregular wave spectra (Hs=13.5 m, Tp=12, 14 and 16 s). The water depth was 150 m.

NOMENCLATURE
a-c = parameters in expression for probability of exceedence
Cd = drag coefficient
fb = freeboard height from still waterline in m
f = force on slender structures per metre length in kN/m
F = force on slender structures due to transverse flow in kN
RELATIVE WAVE MOTIONS ALONG THE SIDE OF A HULL

Calculated linear relative wave motions

The relative motions of the waves with respect to the ship are defined as the difference between the local vertical vessel motion \( z \) (including heave, pitch and roll) and the local wave motions \( \zeta \) according to:

\[
r = \zeta - z
\]

FPSO motions and relative wave motions are nowadays generally calculated with linear (3D) diffraction analysis. Diffraction analysis is based on the main assumptions of small sinusoidal incoming waves, small vessel motions and an evaluation of the fluid-structure interaction only up to the still waterline. Based upon these assumptions it is possible to linearize the problem. Therefore the relation between the ship or relative wave motion amplitude and the incoming wave amplitude can for each frequency be expressed in the frequency domain as a linear Response Amplitude Operator (RAO). In Figure 3 a comparison is made between the calculated and measured relative motion RAO at position R10 along the side of the ship in regular waves. This comparison is reasonably good. It should be noted, however, that it is based on the first harmonic amplitudes of the input wave and relative wave motions. In reality the input and output signals contained also significant higher harmonics.

The RAOs from diffraction theory can be used to determine the relative wave motion response in an irregular wave spectrum (defined by its standard deviation \( s \)). Applying the assumptions of a narrow banded linear motion response to Gaussian distributed waves, Ochi [8] developed the following expression for the probability of exceedence \( P \) of a certain value \( R \) of a peak of the relative wave motions:

\[
P(r > R) = \exp \left( -\frac{R^2}{2s^2} \right)
\]

By replacing the value \( R \) by the freeboard height \( f_b \), the probability of exceedance of the freeboard can be determined if the applied assumptions hold true.

Measured non-linear relative motions along the side

However, it was found in the model tests that the relative wave motions are in reality significantly non-linear. In Figure 4 the probability of exceedence of the relative motions at point R11 is shown in the wave spectrum of \( H_s=13.5 \) and \( T_p=14.0 \text{s} \) (wave heading 210 degrees). The figure shows both the linear narrow banded Rayleigh distribution (expression 2, dotted line) and the measured probability of exceedence curve (solid line). It will be clear that the Rayleigh distribution underestimates the extreme relative wave motions significantly.

Also the measured number of extremes was much larger than predicted based on the total test duration and the mean calculated relative motion period in the spectrum. In Table 2 a comparison is made for the calculated and measured numbers of extremes for the 210 degrees heading. The number of measured extremes is much larger than the calculated number, especially for the longer waves. Together with the measured shape of the probability of exceedence, this points to a strong non-linearity in the results and the existence of higher order (such as double frequency) effects.

Observations of relative motions along the side

From a detailed study of the behaviour of the (relative) waves along the side of the ship from video recordings, it became clear that the (relative) wave crests tend to be more and more peaked when the wave peaks travel aft along the side, as shown schematically in Figure 1. This is a result of the fact that the
higher harmonic components in the wave become more important after reflection of the wave on the hull, as will be discussed later. Typically at midships (of slightly further aft) the peaks become so high that they exceed the freeboard level. The roll motions of the vessel are still very moderate in this condition.

At the moment that the relative wave motions exceed the freeboard, there occurs a surprisingly fast transverse flow over the deck. The water on the deck does not travel mainly with the velocity of the (orbital) motion of the wave crest along the side, but has a dominant component perpendicular to the length of the ship. This large velocity transverse flow results in the main loading from green water from the side. The transverse flow onto the deck shows much resemblance with the water behaviour after the breaking of a dam. This will be discussed later in more detail.

**PHYSICAL BACKGROUND OF OBSERVED BEHAVIOUR**

The strong non-linearity in the relative wave motions is confirmed by the time traces of the regular wave tests. The time traces in Figure 5 show the relative motions at positions R10, R11 and R12 together with the wave input signal for a wave period of 14.44 s (λ/L=1.25). It should be noted that the wave signal is measured during the test and contains reflections from the model.

The time traces show significant double frequency effects compared to the input wave frequency. This is confirmed by the harmonic analysis of the signals, as summarized in Table 3, together with that of the input wave signal. The second harmonics with their double frequency are of similar magnitude as the first harmonics.

The background of these effects lays in the higher harmonics in the input wave, which are bounded to the first order wave. They result themselves already in higher wave crests than troughs [7]. However, in the presently studied conditions with waves slightly off the bow, they reflect on the side of the ship and are amplified significantly compared to the first harmonic amplitudes of the input wave and relative wave motion.

In the typical relative motion RAO in Figure 3 it was found that for higher frequencies the response (amplitude amplification) is around two, whereas at the longer wave frequencies the response is very small. If we assume that the response of the different harmonics can be handled separately, this implies that higher harmonic frequencies in the input (wave) signal become much more important in the output (relative motion) signal.

As an example the response at the first and second harmonic frequencies at position R10 is shown in Table 4 for the first harmonic wave frequency of 0.435 rad/s. The table shows a good comparison with the measured responses for the first and second harmonics. Although this effect requires further study, it is presently assumed that this is the reason for the importance of the higher harmonics in the longer waves. For the shorter waves this effect is less important because of the higher first order (linear) response.

**DESCRIPTION OF NON-LINEAR RELATIVE WAVE MOTIONS**

With higher order diffraction theory it will be possible to predict the first and higher order response of the relative wave motions along the side theoretically. Using higher order Volterra type modelling methods similar to those used by Adegeest [1], it will then be possible to describe the non-linear distribution of the extremes.

In the present study, however, an approach was chosen which was successfully applied for the relative motions in front of the bow [3]. To describe the non-linear distribution of extremes for the relative wave motions in the side, a modified Rayleigh distribution is defined, using the standard deviation from the linear diffraction calculation as starting point again.

\[
P(r > R) = \exp\left(-\frac{R^2}{2\sigma_r^2}\right) \left(1 + \frac{a + b \cdot R + c \cdot R^2}{\sigma_r^2}\right)\]

(3)

This expression, which is a clear modification of expression 2, is now fitted to the measured distribution. This fitting was carried out for both wave directions of 195 and 210 degrees and for all spectral peak periods of 12, 14 and 16 seconds. In Figure 6 an example is shown for position R10 and a wave direction of 210 degrees.

With the new expressions for the probability of exceedence design values for the maximum relative wave motions can be determined, such as the Most Probable Maximum (MPM) value. The MPM value is the relative wave motion value for which the following relation applies:

\[
P(r > R_{\text{MPM}}) = \frac{1}{N}
\]

(4)

N is the total number of relative motion maxima in the total storm duration. It should be noted that, to determine the most probable maximum relative motion, the number of oscillations cannot be simply determined from the mean period. A correction should be applied to take into account the higher harmonic response. At present the following correction is proposed based on the results in Table 2:

\[
N_n = \eta \cdot N
\]

(5)

N is the number of extremes based on the mean period of the linear motion response, N_n is the actual number of extremes in the non-linear situation. In Table 5 an approximation of the factor \(\eta\) is proposed based on the mean values of the calculated and measured values of N.
GREEN WATER FLOW AND LOADING FROM THE SIDE

Transverse water flow onto the deck

The flow of greenwater from the side is a complex process. During the observations described earlier, it was found that there occurs a surprisingly fast transverse flow over the deck when the relative wave motions exceed the freeboard. The water on the deck does not travel mainly with the velocity of the (orbital) motion of the wave crest along the side, but has a dominant component perpendicular to the length of the ship.

During the model tests, measurements were carried out with an empty deck and 5 water height probes (HPROFILE 1-5) at equidistant positions over the beam of the vessel (see Figure 1). In Figure 7 an example of the time traces of these measurements is given for one green water event from the side. From these time traces the (parabolic) decrease in water height from the side can be observed, as well as the transverse velocity of the water front over the deck (by dividing the distance between the probes by the time necessary for the waterfront to travel from one to another). For this case the transverse velocity of the waterfront U is 16.8 m/s for a water height on the side h (approximately equal to the exceedance of the freeboard) of 3.4 m.

Hydraulic models for greenwater flow from the side

The knowledge about the complex physics of green water flow from the sides onto the deck is limited. However, from the observations it became clear that the flow onto the deck shows much resemblance with the water behaviour in the theoretical dambreaking problem. This was also observed for the flow onto the deck at the bow [2].

The theoretical dambreaking problem is described extensively by Stoker [9], using shallow water wave assumptions. In the theoretical dambreaking problem there is a vertical wall of water of height h’ at t=0 (see Figure 8). At that moment the imaginary dam is taken away and the water flows into the dry area. Based on shallow water flow assumptions, Stoker determined the following expression for the water height H(y,t) at time t and position y from the initial dam position with an initial height h’ (not valid for t=0):

\[ H(x,t) = \left( \frac{y}{3} \frac{g}{\sqrt{2}} \frac{t}{2} + \frac{2}{3} \sqrt{h'} \right)^2 \]  

(6)

In Figure 9 an example water contour (at a certain time) is shown of the water flow onto the deck of the FPSO. The input parameter is the exceedance of the freeboard h. However, this h is not equal to the initial dam height h’ in expression 6. The latter value is equal to h=4/9h’ and can be explained from Figure 8: after the breaking of the dam a depression travels into the water area. The water contours rotate around the point of the initial dam position at a height that is 4/9 of the original water height h’ of the dam. To apply the dambreaking theory to the green water problem from the side, the value h’ in expression 6 should not be taken as the freeboard exceedance (h), but as:

\[ h' = \frac{2}{9} h \]  

(7)

Finally it should be noted that expression 6 is based on the assumption that the amount of water on the water side is infinite and without initial velocity. In the green water case the fluid flow in the (relative) waves is fully dynamic and only occurs for a short time duration.

Taking into account these assumptions, it is still clear that the theoretical dambreaking problem provides a good general model of the flow of the green water from the deck. It allows us to understand typical flow behaviour and estimate load levels. This is confirmed for instance if we compare the velocities of the green water flow from the side from Figure 7 (U=16.8 m/s for an approximate freeboard exceedance of h of 3.4m) with the theoretical velocity of the water front U at the deck level based on the dambreaking problem, which can be expressed as:

\[ U = 2 \sqrt{gh'} \]  

(8)

This results (taking into account expression 7) a theoretical front velocity U of 17.3 m/s, which is very close to the measured velocity.

With the dambreaking model as basis, it is now possible to study the typical flow behaviour on the deck as a result of greenwater from the side. Figure 10 can then be considered as the transverse flow onto the deck of an FPSO after the exceedance of the freeboard level by 3.4 m. The horizontal axis can be seen as the deck level and the vertical axis as the position of the original dam, as shown in Figure 9. The contours show the water profile on the deck at different time steps (t=0.09, 0.11, 0.13 s,…). In the figure a vertical pipe is placed at 1.0 m from the side of the ship. In the next section the typical load levels on this pipe will be calculated. To do this, knowledge of the velocity distribution in the water at this position is necessary.

The velocity of the water particles u in the flow (different from the front velocity U), can according to [9] be expressed as:

\[ u = 2 \left( \frac{y}{t} + \frac{u}{\sqrt{gh'}} \right) \]  

(9)

It is important to note that dambreaking flow (and greenwater flow) can be considered as a shallow water wave. This implicates that the velocity distribution over the height of the flow at one point is considered to be constant, as indicated in Figure 9. Expression 9 consequently gives the horizontal velocity of the
flow at time \( t \) and position \( x \) over the complete height of the flow \( H \).

Because in the next section the maximum total load on the pipe has to be determined, it is convenient to determine the velocity as function of the water height on the deck \( H \) and independent of time. To achieve this, it should be noted that expression 6 can be modified to:

\[
\frac{y}{t} = -3\sqrt{g \cdot h} + 2\sqrt{g \cdot h'}
\]  

(10)

Which results in a horizontal velocity as function of water height on the deck as:

\[
u(H) = 2\sqrt{g \cdot h' - \sqrt{g \cdot H}}
\]  

(11)

It will be clear from this expression that this flow velocity with a certain water height \( H \) on the deck is significantly lower than the initial (water front) velocity, see Figure 10. This has an impact on the loading on structures at the deck, which will be discussed next.

**Green water loading from the side on slender structures on the deck**

In the model tests carried out in the JIP it was found that the loading of green water on slender structures is dominated by the drag load as a result of the high velocities involved and hardly influenced by impact type of phenomena (involving a significant effect of the structure on the change of momentum in the flow). The load \( f \) on a slender structure can therefore be expressed per metre length as:

\[
f = \frac{1}{2} C_d \rho D u^2
\]  

(12)

Typical \( C_d \) values for different structural shapes can be found in standard text books (\( C_d = 1.1 \) for a circular pipe).

Using this equation and the considerations on the dambreaking flow above, the total sideways load \( F \) on a vertical pipe close to the deck edge (as in Figure 10) can be estimated. First we consider that the (drag) load on the pipe due to the green water is constant over the total height of the green water layer with height \( H \). This is due to the fact that the water velocity is constant over this height. The total load on the pipe can therefore be written as:

\[
F = \frac{1}{2} C_d \rho D u^2 H
\]  

(13)

Including now the velocities from expression 11, the total load on the pipe as function of the water height at the position of the pipe can be expressed as:

\[
F(H) = 2C_d \rho g D (h' - 2\sqrt{h'H} + H)H
\]  

(14)

Taking half the local water height \( H \) as the moment arm with respect to the deck level (valid based on the shallow water assumptions) the moment on the pipe becomes:

\[
M(H) = C_d \rho g D (h' - 2\sqrt{h'H} + H)H^2
\]  

(15)

In Figure 11 these expressions are now plotted as function of the water height on the deck. From this figure it becomes clear that both the water height \( H \) and the water velocity play a role in the loading on the pipe. With a thin layer of water on the deck the water velocity is high (expression 11), but it only integrated over a very small height \( H \). With higher water heights, the water velocity is reduced such that the total load is decreasing again.

In the presented case (\( h' = 3.4 \text{ m}, D = 0.3 \text{ m}, x = 1.0 \text{ m}, C_d = 1.1 \)) the maximum loading occurs at the moment that the water height \( H \) is 1.91 m, whereas the moment is the highest when the water height is 3.4 m. Stress analysis in the pipe will have to show which combination of load and moment is the most critical for the pipe.

By differentiation of expressions 14 and 15 with respect to the waterheight on the deck \( H \) and determining the maxima, the waterheight on the deck \( H \) at which the highest total load and moment occur can be found:

\[
H_f_{\text{max}} = \frac{1}{4} h'
\]  

(16)

\[
H_{M_{\text{max}}} = \frac{4}{9} h'
\]  

(17)

This, combined with expression 7, finally allows us to define the estimated maximum load and moment on the pipe as function of freeboard exceedance \( h \) only:

\[
F_{\text{max}} = \frac{81}{128} C_d \rho g D h^2
\]  

(18)

\[
M_{\text{max}} = \frac{1}{4} C_d \rho g D h^3
\]  

(19)

In the expressions above the effect of the longitudinal flow velocity as a result of the orbital motions in the wave crest, is still neglected. This longitudinal flow was observed during model tests and results in an additional load component.

If this additional longitudinal flow velocity \( v \) is also taken into account, the resulting total velocity is not perpendicular to the length of the ship anymore, but under an angle. The total resulting velocity \( V \) can simply be found by:

\[
V = \sqrt{u^2 + v^2}
\]  

(20)

Taking into account that the load process (expression 12) in the direction of the flow is quadratic with the resulting speed \( V \), it is
found that the load contributions of the transverse flow velocity \(u\) and longitudinal flow velocity \(v\) can be determined separately and added afterwards (assuming a constant \(C_d\) in all directions). The effect of the transverse flow component \(u\) was determined in expressions 18 and 19, now the additional terms as a result of the longitudinal flow component \(v\) are derived.

First the orbital velocity in the wave is estimated. Because no water can flow through the hull of the vessel, the orbital velocity of the waves along the hull will be along the length of the ship, even with wave headings slightly off the bow. The amplitude of the relative wave is equal to the freeboard \((fb)\) plus the exceedance of the freeboard \((h)\). Neglecting the effect of the ship motions on the relative motions, based on linear theory the horizontal velocity in the wave crest can now be expressed as function of the wave period \(T\):

\[
v = \frac{2\pi \cdot (h + fb)}{T}
\]

(21)

With expression 13 (and taking the moment arm \(1/2H\) again) the load components due to the longitudinal velocity component can now be determined (for \(h>0\)):

\[
F' = 2C_d \rho D \frac{\pi^2}{T^2} (h + fb)^2 H
\]

(22)

\[
M' = C_d \rho D \frac{\pi^2}{T^2} (h + fb)^2 H^2
\]

(23)

To determine the additional effect of the longitudinal flow component on the maximum force and moment on the slender vertical structure, expressions 7, 16 and 17 are now included in the expressions above.

\[
F_{\text{max}}' = \frac{9}{8} C_d \rho D \frac{\pi^2}{T^2} (h + fb)^2 h
\]

(24)

\[
M_{\text{max}}' = C_d \rho D \frac{\pi^2}{T^2} (h + fb)^2 h^2
\]

(25)

These expressions for the longitudinal flow component contribution should be added to expressions 18 and 19 for the transverse flow component contribution to find the total loads on the slender vertical structures. It should be noted that the direction of the loading is in the direction of the resultant velocity \(v\) in expression 20.

The example of the load process as discussed in this paper, can also be used for other types of vertical slender structures, using their specific \(C_d\)-values.

The load on larger structures requires a different approach because the main loading on the structure is a result of the momentum in the green water flow which is completely deflected by the structure. General models for this type of loading can be found in [4-6,10-11].

CONCLUSIONS

Based on the results and discussions in this paper, the following conclusions seem justified:

- Green water loading from the side is an important safety problem and needs to be evaluated in the design of FPSOs.
- The strongly non-linear relative wave motions along the side of the hull are a result of non-linearities in the incoming waves and in the reflection of the waves on the side of the ship. The developed expression allows the determination of the extreme relative wave motions and possible related freeboard exceedances.
- The application of the theoretical dambreaking problem to the flow onto the deck is helpful for the estimation of the load levels on slender structures on the deck, close to the side of the FPSO.

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REFERENCES

Table 1: Main particulars of the tested FPSO

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<td>Beam</td>
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<td>Depth</td>
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<td>Draft (even keel)</td>
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<td>Transverse metacentric height (GM)</td>
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<td>Roll radius of gyration</td>
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Table 2: Calculated (linear) and measured number of extremes in a 3 hours storm

<p>| | | | |</p>
<table>
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<tr>
<th></th>
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<td></td>
<td>$T_p = 12$ s</td>
<td>$T_p = 14$ s</td>
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<td>Linear</td>
<td>Meas.</td>
<td>Linear</td>
<td>Meas.</td>
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<tr>
<td>R9</td>
<td>1074</td>
<td>1279</td>
<td>973</td>
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<tr>
<td>R10</td>
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<td>1231</td>
<td>929</td>
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<td>R12</td>
<td>1072</td>
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Table 3: Harmonic analysis of input wave and output signals in a regular wave test

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<th>First harmonic amplitude in m ($T=14.44$ s)</th>
<th>Second harmonic amplitude in m ($T=7.22$ s)</th>
<th>Third harmonic amplitude in m ($T=4.81$ s)</th>
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<tr>
<td>Wave input</td>
<td>11.45</td>
<td>0.89</td>
<td>0.71</td>
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<tr>
<td>R10</td>
<td>2.12</td>
<td>1.73</td>
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<tr>
<td>R11</td>
<td>1.75</td>
<td>2.37</td>
<td>0.81</td>
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<td>R12</td>
<td>1.81</td>
<td>2.04</td>
<td>0.76</td>
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Table 4: Response at position R10 of first and second harmonics with linear RAO

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Wave frequency (rad/s)</th>
<th>Amplitude (m)</th>
<th>$\omega_n$ (rad/s$^2$)</th>
<th>Response</th>
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<td>First</td>
<td>0.435</td>
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<td>Second</td>
<td>0.87</td>
<td>0.89</td>
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Table 5: The non-linearity correction factor for the number of extremes

<table>
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<tr>
<th>Peak period</th>
<th>Factor $\eta$</th>
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<tr>
<td>12 s</td>
<td>1.27</td>
</tr>
<tr>
<td>14 s</td>
<td>1.65</td>
</tr>
<tr>
<td>16 s</td>
<td>1.60</td>
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Figure 1: Typical progressing wave along the side of the FPSO

Figure 2: Body plan of tested FPSO hull

Figure 3: RAO and phase of relative wave motion at position R11 with 210 degrees wave heading (calculations as solid line, regular wave tests as points)
Figure 4: Comparison of linear (narrow banded) Rayleigh distribution (dotted line) with measured probability of exceedance (solid line) for R11

Figure 5: Time traces of incoming wave (WAVE 1) and R10-R12 for a regular wave period of 14.4 s, showing clear higher harmonic responses

Figure 6: Modified Rayleigh distribution fits for R11 in spectral peak periods of 12 s (top) and 16 s (bottom)

Figure 7: Time traces of the water height on the deck at several (equidistant) positions over the beam of the FPSO
Figure 8: Theoretical dambreaking problem

Figure 9: Application of dambreaking problem to green water flow from the side onto the deck

Figure 10: Water contours at time steps t=0.09s, 0.11s, 0.13s, ... for a freeboard exceedance of 3.4m

Figure 11: Water particle velocity as function of water height on the deck (freeboard exceedance 3.4m)

Figure 12: Load on a vertical pipe (D=0.3m) as function of water height H due to transverse flow
Figure 13: Moment on a vertical pipe (D=0.3m) as function of water height H due to transverse flow