20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Numerical Investigation of Green Water for A Two Dimensional Fixed Rectangular Structure

Xiantao Zhang[1], Scott Draper[1], Hugh Wolgamot[1], Wenhua Zhao[1], Liang Cheng[2] and David White[1]

[1]Center for Offshore Foundation Systems, University of Western Australia, Western Australia, 6009, Australia

[2]School of Civil, Environmental and Mining Engineering, University of Western Australia, Western Australia, 6009, Australia

Abstract

This paper presents results from a numerical study of wave overtopping leading to the occurrence of green water on a two-dimensional fixed rectangular structure, representative of a large ship. The problem is investigated using Computational Fluid Dynamics (CFD) with a Volume of Fluid (VOF) surface capturing scheme. Validation of the CFD model has been made with linear potential flow theory for small wave steepness and existing experimental measurements for larger wave steepness. The model has then been used to investigate overtopping events resulting from incident focused wave groups (representative of a NewWave type focused wave group) for a range of wave parameters. In agreement with Greco et al. [4] a range of overtopping events have been identified across this parameter space, including dam-break (DB) type, plunging plus dam-break (PDB) type, hammer-fist (HF) type and plunging wave (PW) type overtopping. The flow of green water on deck resulting from overtopping is divided into a transition zone and a “dam-break” zone (in which the water front velocity is almost constant). The water front velocity in the dam-break zone is investigated and summarized for the different types of overtopping events. Results show that the traditional design procedure may overestimate the green water loads, especially for PDB and DB events, by assuming the dam height to be freeboard exceedance in classic dam-break solution.

Introduction

Green water events (in which a compact mass of water exceeds the freeboard and flows onto the deck) in harsh sea conditions have become a critical issue for offshore structures as they can cause damage to the deck, superstructure and equipment, as well as reduce the dynamic stability of offshore floating facilities.

Much early work on green water has made use of the fact that flow onto the deck resembles a dam-break. This similarity between shipped water flow and dam-break flow was first observed by Buchner [2] and further investigated by Ryu et al. [9]. Based on the similarity, the traditional design procedure to estimate green water flow on deck makes use of an analytical dam-break solution (Ritter [8]) with the initial height of the reservoir equalling the free-board exceedance (Schonberg and Rainey [10]). Greco et al. [3] studied both numerically and experimentally green water incidents for a two-dimensional fixed FPSO model. They observed in their model test that the water shipping started as a plunging wave hitting the deck and entrapping air, but then evolved into a dam-break like flow along the deck. The problem was further investigated by Greco et al. [4]. In that work, an attempt was made to classify green water events into different wave overtopping types, including:

- dam-break (DB) type
- plunging plus dam-break (PDB) type
- plunging wave (PW) type
- hammer fist (HF) type
- (flip through without water on deck or white water type).

The classification was performed in terms of two parameters, i.e. incoming wave steepness and the ratio $(W_w)_{max}/W_{max}$ (W_{max} denoting the maximum wave vertical velocity at the leading edge and $(W_w)_{max}$ representing the maximum vertical velocity at a specific position in front of the leading edge).

These wave overtopping types may be important for offshore engineers if they are related to the flow characteristics and, ultimately, impact loads, i.e. the severity of damage to offshore structures. However, some limitations exist for the (admittedly only schematic) classification conducted by Greco et al. [4]. The incident waves adopted in the work were regular waves with an initial transient, for which the shape of the wave envelope bears no specific relation to those which might be expected to cause green water in the open sea. Further, the ratio $(W_w)_{max}/W_{max}$ (without correlation with wave and ship parameters) provides very limited information in the design process and it is difficult to determine a reasonable location where $(W_w)_{max}$ is calculated for different wave and ship parameters.

The present study aims to tackle the above-mentioned limitations of the green water classification of Greco, and to determine whether the different types of event would be expected to be associated with different flow and load profiles. A two-dimensional fixed rectangular box is the structure of interest (perhaps representing an offshore facility like an FPSO, for which forward speed is not relevant). The incident waves are focused wave groups based on the NewWave formulation (Tromans et al. [11]), which represent the most probable free surface elevation around a large crest and include much of the spectral properties of the underlying random sea state. The problem is investigated using Computational Fluid Dynamics (CFD) with a Volume of Fluid (VOF) surface capturing scheme (Hirt and Nichols [5]). Validation of the CFD model has been made with linear potential flow theory for small wave steepness and existing experimental measurements for larger wave steepness. Based on numerical results covering a wide parameter space, wave overtopping types are classified directly in terms of the relative height and length of the incident wave group. Some key features of green water are reported.

Numerical Method

The numerical wave tank (NWT) is established based on numerically solving the incompressible Navier-Stokes equations for a two phase flow of water and air with the implementation of a VOF (Volume of Fluid) scheme for tracking the free surface (Hirt and Nichols [5]). The governing equations are solved by the finite volume method, which is discretised on a structured multi-block mesh within the framework of the open source Computational Fluid Dynamics (CFD) toolbox OpenFoam® of version 2.4.0. The numerical model is combined with the fully nonlinear wave generation and absorption utility waves2Foam (Jacobsen et al. [6])

to perform numerical simulations of green water overtopping onto a fixed two dimensional rectangular structure.

NewWave type focused wave groups (Tromans et al. [11]), correct to second order, are adopted. The input signal for the CFD runs is the sum of the first and the second order component of the horizontal and vertical velocity component and the surface elevation (refer to Ning et al. [7]). The relaxation technique, which is inherent in the wave generation tool waves2Foam, is used to avoid the reflection of waves from the outlet boundaries.

Validation of the Numerical Model

Validation has been carried out by considering three aspects of the numerical model:

(1) Green water usually occurs under large waves, in which condition the nonlinearity, especially the second order sum-frequency contribution, significantly influences the crest of waves. For this reason the second order frequency components associated with a focused wave group have been analysed in the NWT. Specifically, both crest- and trough-focused wave groups have been simulated and used to extract the even harmonics. Then the second order sum and difference frequency terms are calculated by band-pass filtering the even harmonics. The second order term can also be calculated by combining the linear time series and its Hilbert transform (e.g. Walker et al. [12]). Results obtained by using the two approaches are compared and the agreement is good. This provides confidence in the ability of the NWT to accurately simulate the nonlinear second order contribution.

(2) CFD-generated free surface elevations have been compared to results from linear potential flow theory for interaction of NewWave groups of small wave steepness with a rectangular box. Good agreement is obtained (in the absence of overtopping).

(3) CFD results have been compared to experimental measurements (Greco et al. [3]) for the interaction of waves having larger wave steepness with a rectangular box. The agreement is also satisfactory.

Due to the limited number of pages in this manuscript, several figures indicating the good agreement are not included in this section but will be shown in the presentation.

Results and Discussion

The dimensions of the rectangular structure are summarized as follows: L/D=15 and f/D=1/4 (L, D and f are, respectively the length, draft and freeboard of the rectangular structure; see Fig.1). In the CFD simulations the draft, D, is 0.2 m. The water depth, h, is set equal to the peak wave length, λ_p, of the incident focused wave group to ensure deep water conditions.

The wave conditions are given in Table 1. A JONSWAP spectrum is adopted in this study with peak enhancement factor, γ, of 3.3. Due to the nonlinear interaction of wave components, the actual focal position is different from the input one (e.g. Ning et al. [7]). In our calculation the actual focal position is determined by searching for the maximum peak crest along tank. Subsequently,

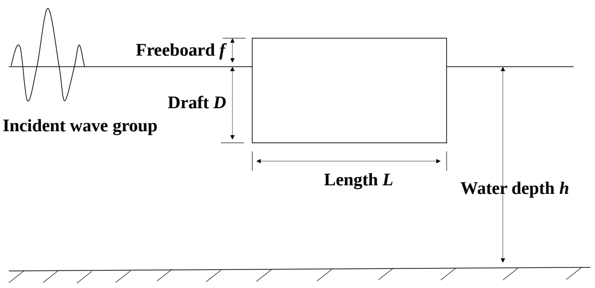

Figure 1. Schematic of the interaction of incident focused wave groups with a rectangular structure.

λ_p/D	f_p (Hz)	f_1 (Hz)	f_2 (Hz)	N	$A_{I,l}/\lambda_p$
5	1.230	1.04	1.6	57	0.03,0.025
6	1.141	0.94	1.46	53	0.03,0.025,0.02
7	1.056	0.86	1.4	55	0.035,0.03,0.025,0.02
8	0.988	0.8	1.3	51	0.035,0.03,0.025,0.02
10	0.883	0.7	1.24	55	0.035,0.03,0.025,0.02
12	0.807	0.64	1.12	49	0.035,0.03,0.025,0.02
15	0.722	0.58	0.96	39	0.035,0.03,0.025,0.02,0.01
22	0.596	0.48	0.8	33	0.035,0.03,0.025,0.02,0.01
30	0.510	0.4	0.7	31	0.03,0.025,0.02,0.01

Table1. Wave conditions for CFD simulations. λ_p and f_p are, respectively, the peak wave length and peak frequency of focused wave groups. f_1 and f_2 are respectively, the lower and upper limit of the frequency bandwidth. $A_{I,l}$ is the linear peak crest of incident focused wave groups.

the rectangular structure is placed in the NWT with the leading edge being at the actual focal position of the incident wave group.

Profiles of Different Wave Overtopping Types

Indicative profiles for different wave overtopping types are given in Fig.2. For a DB event (Fig.2(a)), a small amount of water ships onto the deck without showing any visible plunging. The free surface elevation is close to horizontal offshore from the leading edge of the structure. For a PDB event (Fig.2(b)), the water shipping starts as an initial plunging event with an air cavity entrapped on the deck. The maximum wave elevation occurs somewhere in front of the structure. As shown in Fig.2(c), the HF green water exceeds the freeboard in the form of a fluid arm with almost unchanged direction and thickness until gravity starts to dominate. Then the water ships onto the deck bluntly without forming any visible air cavity. The wave elevation reaches its maximum value at the bow or on the deck but becomes smaller in front of the structure. For a PW event the plunging phase has a large spatial scale and characterizes the whole water-on-deck event. The initial plunging length is around 1.5D (D is the draft), which is much larger than that of a PDB event (0.2D for PDB shown in Fig.2(b)). Due to the violent wave structure interaction, the air cavity entrapped extends from deck to the front edge of the ship for a PW event.

The velocity field (especially near the intersection of the front edge and deck) is also quite different at the instant when water shipping onto deck occurs. For DB, the velocity near the deck is upward and slightly diverted towards the deck. For PDB, the velocity is also upward and much more diverted towards the deck than DB. However, for HF, the velocity becomes downward. The velocity near the front edge for PW is also in the upward direction. The plunging jet partly moves backwards, which is different from PDB.

Classification of Different Wave Overtopping Types

The set of parameters (including both wave and ship parameters) that may affect the wave overtopping type are summarized as follows: $A_{I,nl}$ (the undisturbed nonlinear peak crest at the actual focal position), λ_p, L, D, f, h. For deep water conditions the effect of water depth, h, may be neglected. Furthermore, according to potential flow results (which are not shown here), the effects of ship length on the maximum wave elevation at the leading edge of the structure is insignificant for $L/D\geq15$ (which is typical of an FPSO [13]). Thus only four parameters - $A_{I,nl}$, λ_p, D, f - are considered here. By dimensional analysis, these four dimensional parameters correspond to three non-dimensional parameters. We choose $A_{I,nl}/\lambda_p$, λ_p/D and $A_{I,nl}/f$. The first of these, $A_{I,nl}/\lambda_p$, represents the incident wave steepness. The second, λ_p/D, encapsulates wave diffraction due to the existence of the structure and may be related

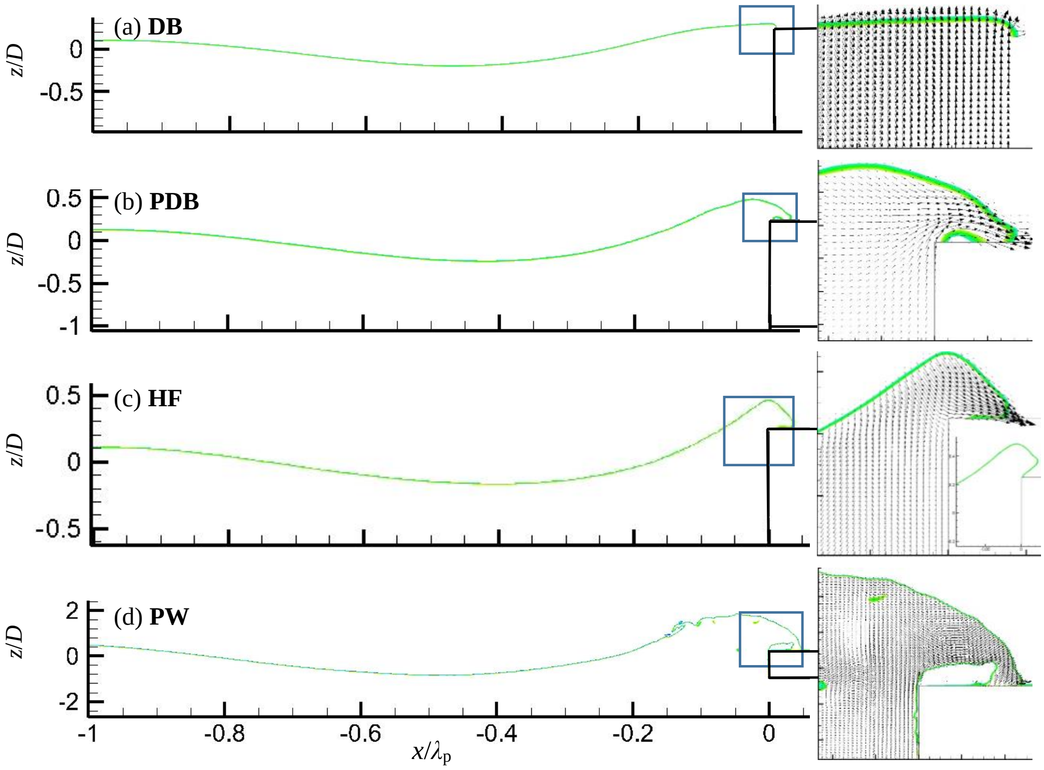

Figure 2. Profiles of different wave overtopping types: (a)DB, λ_p/D=15, $A_{I,l}/\lambda_p$=0.01; (b)PDB, λ_p/D=8, $A_{I,l}/\lambda_p$=0.025; (c)HF, λ_p/D=5, $A_{I,l}/\lambda_p$=0.03; (d)PW, λ_p/D=30, $A_{I,l}/\lambda_p$=0.03. Note: in Fig.2(c), the profile in the inset is 0.04s ahead of the larger one.

to the ratio $(W_w)_{max}$ /W_{max} according to potential flow results (which are also not shown here) (Greco et al. [4]). $A_{I,nl}/f$ is expected to correlate with the freeboard exceedance.

The classification of different wave overtopping types in terms of the above-mentioned dimensionless parameters is given in Fig.3. Note that PHF is the abbreviation for 'Plunging plus Hammer Fist' (the profile is not given here but will be shown in the presentation). This can be seen as a transitional overtopping event with characteristics similar to that observed in both HF and PDB events. Overall, the parametric plane of wave overtopping types presented here resembles that proposed by Greco et al. [4] if the ratio $(W_w)_{max}$ /W_{max} is replaced by λ_p/D (which is reasonable given that both these two non-dimensional parameters characterize the local effect of the structure on the wave field). HF type events occur for small wave length and large wave steepness. A long wave of large crest may lead to the occurrence of PW event. DB event tends to occur for small wave steepness (regardless of the incident wave length).

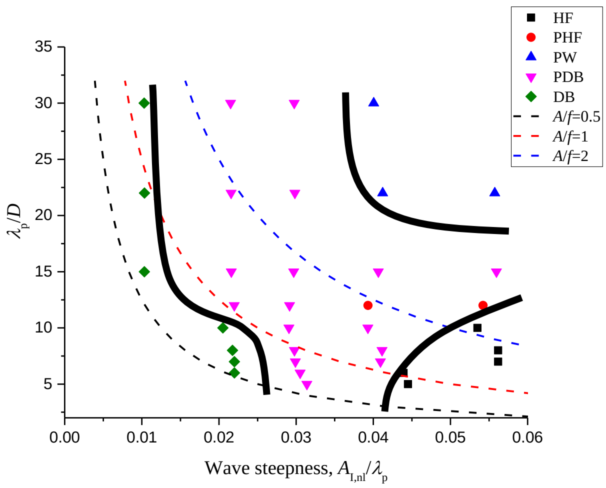

Figure 3. Classification of different wave overtopping types. L/D=15 and f/D=1/4.

PDB, the most common water shipping type, is more likely to be triggered by waves of moderate steepness. The present classification is based on simple wave and ship parameters and can be easily used in design process to classify the features of water-on-deck events.

Water front velocity

In this section, the water front velocity, U_F, is investigated as it has a practical meaning being related to the impact force on superstructures. The water front, x, is measured by a horizontal probe on deck and the front velocity is calculated from the water front time series. As an example, Fig.4 gives the water front and front velocity for a HF type event. It can be seen that the water front velocity oscillates around an averaged value at some distance away from the leading edge (similar to dam-break solution with constant front velocity; Ritter [8]). Similar results are observed for other green water types – i.e. a constant front velocity is achieved. Based on this observation, we divide the deck into two zones: (i) a transition zone; and (ii) a dam-break like zone. The averaged water front velocity in the dam-break like zone are calculated for each of the different water shipping events. As shown in Fig.4, the averaged front velocity is 1.335m/s, which is rather close to the one obtained by linear fitting of the front time series (1.349m/s, the difference is 1%).

The shipped water front velocities for different water overtopping types are summarized in Fig.5. The reference velocity (Fig.5(a)), $2\sqrt{gH_w}$(g is the gravitational acceleration and H_w is the maximum freeboard exceedance), is the water front velocity of a classic dam-break solution with initial height of reservoir equal the freeboard exceedance at the leading edge, H_w. Overall, the ratio of green water front velocity to equivalent dam-break solution is less than 1. On average, this ratio tends to be smallest for a DB event, followed by PDB, PW and then to a HF event. This indicates that the traditional design procedure (using classic dam-break solution with dam height being freeboard exceedance) may overestimate the green water loads, especially for PDB and DB events. Fig.5(b) presents the same data using a different scaling factor. A non-dimensional parameter, $\varepsilon = H_w/\lambda_p$, representative of wave steepness, is introduced (See Barcellona et al. [1]). It can be seen that the non-dimensional water front velocity with wave steepness considered is much more compact (except the DB events), suggesting the influence of wave nonlinearities when shipped water propagates along the deck. The dimensionless front velocity using the new scaling factor shows a different trend, with the result smallest for the PW event, followed by the HF, PDB and then the DB type event.

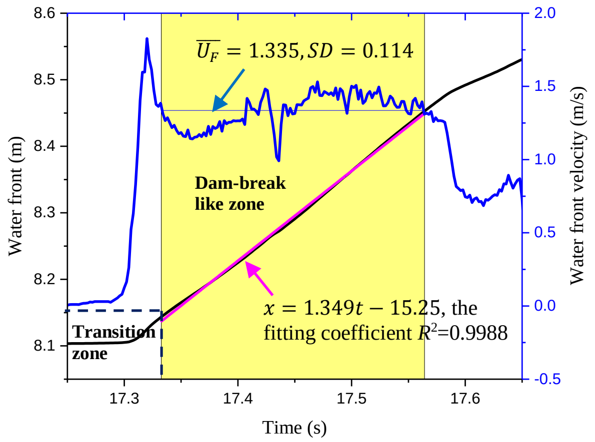

Figure 4. Water front and front velocity for a HF event (λ_p/D=6, $A_{I,l}/\lambda_p$=0.03). Black line: water front. Purple line: linear fitting of black line in region of yellow color. Blue line: water front velocity. $\overline{U_F}$ is the averaged water front velocity and SD is the standard deviation.

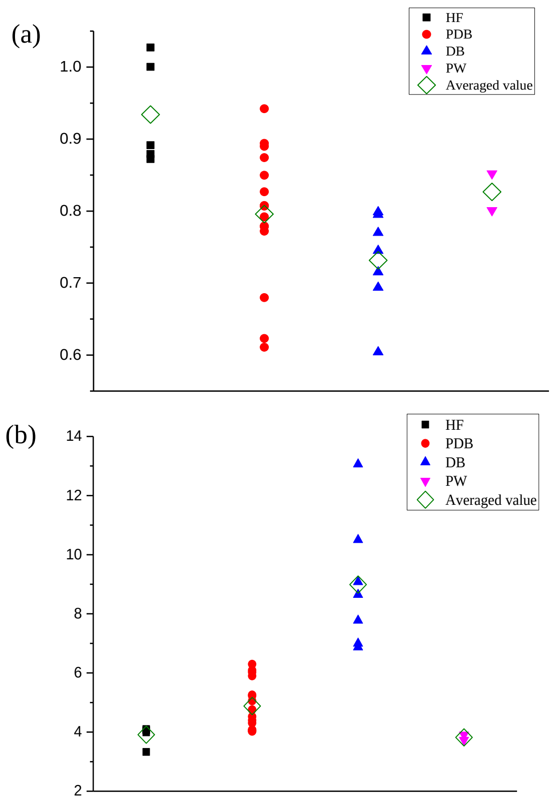

Figure 5. Water front velocity for different water shipping types. (a) The vertical axis: $\overline{U_F}/2\sqrt{gH_w}$; (b)The vertical axis: $\overline{U_F}/2\sqrt{gH_w\varepsilon}$, $\varepsilon = H_w / \lambda_p$

Conclusions

Green water overtopping of a two dimensional fixed rectangular structure under focused wave groups has been investigated using CFD. The profiles and velocity field are presented for four different wave overtopping types, including DB, PDB, HF and PW events. A simple parametric plane for identifying different overtopping events is given based on simple wave and ship parameters. The water front velocity, which is practically related to green water loads on superstructures, has been investigated and summarised for the different overtopping types. Results show that the traditional design procedure may overestimate the green water loads, especially for PDB and DB events, by assuming the dam height to be freeboard exceedance in classic dam-break solution.

Acknowledgments

This work was supported by the ARC Industrial Transformation Research Hub for Offshore Floating Facilities which is funded by the Australian Research Council, Woodside Energy, Shell, Bureau Veritas and Lloyds Register (Grant No. IH140100012) and by resources provided by the Pawsey Supercomputing Centre. The first author would like to acknowledge the support of the IPRS, APA and Shell-UWA offshore engineering PhD research top-up scholarships.

References

[1] Barcellona, M., Landrini, M., Greco, M., & Faltinsen, O. M., An experimental investigation on bow water shipping. Journal of ship research,**47(4)**, 2003, 327-346

[2] Buchner B., The impact of green water on FPSO design. In Offshore technology conference, Houston; 1995.

[3] Greco, M., Faltinsen, O.M., & Landrini, M., Shipping of water on a two-dimensional structure. Journal of Fluid Mechanics, **525**, 2005, 309-332.

[4] Greco, M., Colicchio, G., & Faltinsen, O.M., Shipping of water on a two-dimensional structure. Part 2. Journal of Fluid Mechanics, **581**, 2007, 371-399.

[5] Hirt, C.W., & Nichols, B.D., Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of computational physics, **39(1)**, 1981, 201-225.

[6] Jacobsen, N.G., Fuhrman, D.R., & Fredsøe, J., A wave generation toolbox for the open-source CFD library: OpenFoam®. International Journal for Numerical Methods in Fluids, **70(9)**, 2012, 1073-1088.

[7] Ning, D.Z., Zang, J., Liu, S.X., Eatock Taylor, R., Teng, B., & Taylor, P.H., Free-surface evolution and wave kinematics for nonlinear uni-directional focused wave groups. Ocean Engineering, **36(15)**, 2009, 1226-1243.

[8] Ritter, A., Die fortpflanzung de wasserwellen. Zeitschrift Verein Deutscher Ingenieure, **36(33)**, 1892, 947-954.

[9] Ryu, Y., Chang, K. A., & Mercier, R., Application of dam-break flow to green water prediction. Applied Ocean Research, **29(3)**, 2007, 128-136.

[10] Schoenberg, T., & Rainey, R.C.T., A hydrodynamic model of Green Water incidents. Applied Ocean Research, **24(5)**, 2002, 299-307.

[11] Tromans, P.S., Anaturk, A.R. & Hagemeijer, P., A new model for the kinematics of large ocean waves-application as a design wave. In The First International Offshore and Polar Engineering Conference, 1991.

[12] Walker, D.A.G., Taylor, P.H., & Eatock Taylor, R., The shape of large surface waves on the open sea and the Draupner New Year wave. Applied Ocean Research, **26(3)**, 2004, 73-83.

[13] http://www.offshore-mag.com/content/dam/offshore/print-articles/Volume%2072/aug/2012FPSO-072512Ads.pdf.