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The role of overtopping duration in greenwater loading

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1 Introduction

Greenwater is a critical safety consideration for FPSOs or ship-shaped offshore structures. Due to the complexity of greenwater overtopping, much early work on modelling this phenomenon has made use of the fact that greenwater flow onto the deck somewhat resembles a dam-break [1]. In a simple implementation the analytical dam-break solution [2] is used to estimate greenwater flow on deck given an initial dam height based on peak water elevation in the exterior domain. When comparing to experiments, Buchner [3] argued that the initial dam height should be the experimentally observed freeboard exceedance increased by the factor 9/4 (arising from [1]). In contrast, Faltinsen et al. [4], took the dam height to be the experimentally observed freeboard exceedance but adjusted the time instant of the dam break for each individual event. Such ambiguity arises because much physics in the greenwater event is absent in the dam break solution; e.g. initial water velocities which are non-zero both horizontally and vertically and an overtopping event of finite duration [5].

Greco et al. [6], [7] studied greenwater for a two-dimensional (2D) fixed FPSO model both numerically and experimentally. An attempt was made to qualitatively classify events into different types, for some of which the classical dam break model seems inappropriate. These overtopping types may be important for offshore engineers if they are related to the flow characteristics and, ultimately, impact loads on offshore structures.

The present study aims to quantitatively investigate these different overtopping types, to improve on the simple implementation of the analytical dam break solution to predict the flow and load profiles associated with the different overtopping events. A fixed 2D rectangular box is used to represent a large FPSO. The incident waves adopted are focused wave groups based on the NewWave formulation [8]. The problem is numerically investigated using the OpenFOAM Computational Fluid Dynamics (CFD) scheme with a Volume of Fluid (VOF) surface capturing method. This model has been validated against Greco et al.'s experimental results.

2 Incident wave groups used to simulate overtopping

NewWave type focused wave groups are used to represent the incident waves in this study because they both encompass the spectral and statistical properties of the underlying random sea state and save computational resources. A large wave crest (phase shift φ=0) occurs at the focus position and time (x_f, t_f). The shape of a unidirectional NewWave group is given in linear theory by

$$\eta(x,t)=\frac{A_1}{\sigma^2}\sum_{j=1}^{N}S(\omega_j)\Delta\omega\cos\left(k_j\left(x-x_f\right)-\omega_j\left(t-t_f\right)+\varphi\right) , \tag{1}$$

where $\eta(x, t)$ indicates the free surface profile of the NewWave type focused wave group, A_l corresponds to the expected maximum free surface elevation in a given sea state, $S(\omega)$ is the power spectral density of a given sea state, k_j and ω_j are the wavenumber and circular frequency of the spectral component, and the variance $\sigma^2 = \sum_{j=1}^{N} S(\omega_j)\Delta\omega$. JONSWAP spectral shape with γ=3.3 is adopted.

Boundary conditions to generate focused wave groups have been developed up to second order and added in the framework of waves2Foam [9]. The actual focal position of the undisturbed wave group is determined by choosing the position in the numerical wave tank (NWT) where the maximum peak crest height is achieved. The peak crest height of the incident wave groups at the actual focal position, A_{nl}, is larger than the input linear height A_l. The rectangular box is placed uniquely for each simulation, with the box front coinciding with the actual focal position of the undisturbed wave group.

3 Wave and geometric parameters

We consider a fixed 2D box subject to incident focused wave groups (Fig.1). The box is of length L, draft D and freeboard f, while the wave group parameters are (undisturbed) peak crest height A_{nl} and peak wave length λ_p. We consider non-dimensional ratios of these parameters. We are not interested in finite water depth effects in the exterior domain; hence the water depth is set equal to the peak wave length λ_p so that the waves travel in deep water. We consider the range of freeboard, draft and vessel length of existing FPSOs to motivate our choice of geometry. According to OMO [10], most of the FPSOs in service have an L/D ratio in the range 14-18 and f/D 1/4-1/2. Linear potential flow results (not shown here) indicate the effect of L/D on the maximum free surface elevation at the leading edge of the rectangular box is insignificant for L/D within this range; we therefore choose L/D=15. The lower and upper bound f/D ratios for existing FPSOs, i.e. 1/4 and 1/2 are adopted in the numerical simulation. We also consider a larger freeboard to draft ratio, i.e. f/D=1. Although this value is out of the range of direct relevance to FPSOs, it may be representative of new types of offshore floating facilities such as Floating Liquid Natural Gas (FLNG).

OMO [10] shows that most FPSOs have draft D 10-25 (m). The wave period for a realistic sea state is generally 9-14 (s), corresponding to the peak wave length λ_p being 125-300 (m) in deep water. Thus we take λ_p/D = 5-30. We might expect waves to break when A_{nl}/λ_p = 0.14, or half this value if we consider full reflection, so we choose A_{nl}/λ_p = 0.01-0.06.

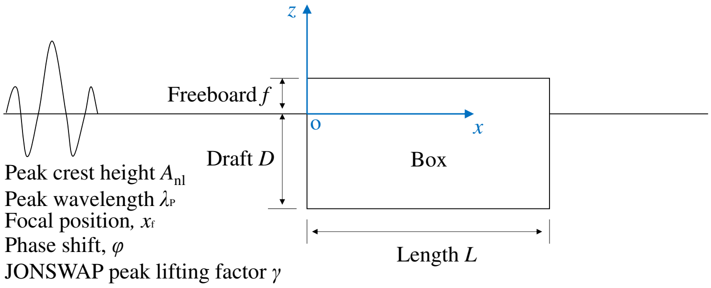

Fig.1 Schematic of the interaction of incident focused wave groups with a rectangular box

4 Classification of greenwater overtopping events

Greco et al.[7] indicated five types of events: dam break (DB), plunging plus dam break (PDB), plunging wave (PW), hammer fist (HF) and flip-through/white water, the former four of which were identified in their experiments. Indicative profiles for these different overtopping types obtained from CFD simulations are given in Fig.2 (a)-(c). Both PDB and PW are characterized by a plunging phase (of different scales) during overtopping. Distinguishing between these scales may be important for topside structures located close to the edge of the vessel. In this work our box has no topside structures and so we choose to categorize PDB and PW into a single type of overtopping event (this type of event is denoted as PDB hereafter).

Fig.2(d) shows a classification of different overtopping types for f/D=0.25 in terms of the dimensionless parameters A_{nl}/λ_p and λ_p/D. A_{nl}/λ_p represents incident wave steepness and λ_p/D is related to wave diffraction due to the existence of the box. The events were classified by visual inspection of movies of CFD results based on the shape of the overtopping. The black curved line is an estimate of the limiting boundary for the onset of freeboard exceedance. Note that the hollow symbols with "+" in the center represent the cases for which the minimum free surface elevation has reached the bottom of the structure and caused slamming on the bow face. These cases are less relevant to wave overtopping on FPSOs and are an artefact of the box fixity. Overall, the parametric plane of wave overtopping types presented here resembles that proposed by Greco et al. [7] if the ratio $W_{W,max}/W_{max}$ (of vertical fluid velocities upstream of and at the bow, respectively) used in that work is replaced by λ_p/D (which is reasonable given that both non-dimensional parameters characterize the local effect of the structure on the wave field). HF events occur for small wavelength and large wave steepness. DB tends to occur for small wave steepness events close to the freeboard exceedance boundary. PDB, the most common water shipping type, occurs everywhere else, between these two extremes.

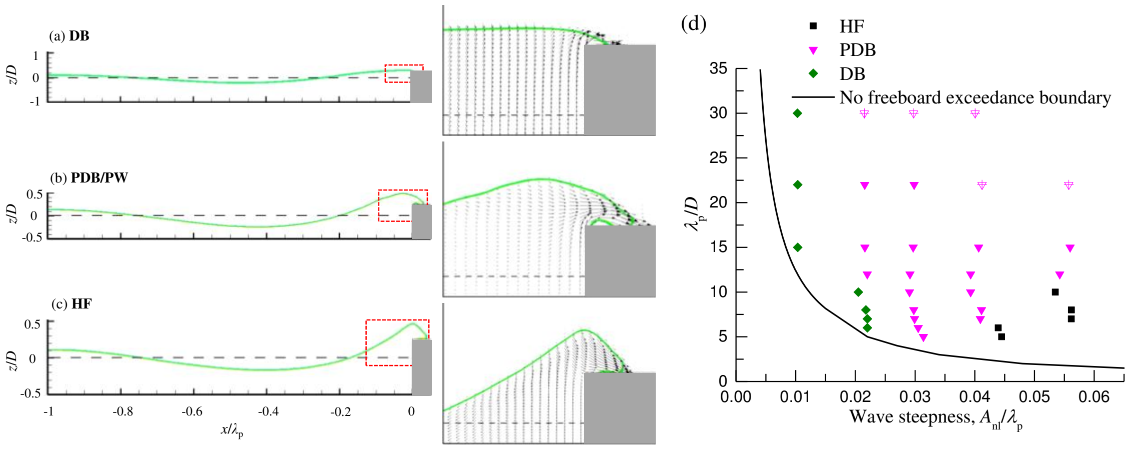

Fig.2 Shipped water profiles (a)-(c), and classification (d) for f/D=0.25. (a)DB, λ_p/D=15, A_{nl}/λ_p=0.01, t/T_p=0.06; (b)PDB/PW, λ_p/D=8, A_{nl}/λ_p =0.03, t/T_p=0.15; (c)HF, λ_p/D=5, A_{nl}/λ_p =0.0445, t/T_p=0.17. t=0 is the time instant when freeboard exceedance occurs. The ratio of the scale between horizontal and vertical axis in (a)-(c) is set as λ_p/D to make wave profiles look undistorted.

5 Momentum flux and duration of overtopping

The momentum flux of water flow on deck is related to the impact force on superstructures. For a classical dam break with an initial height of h_0, the maximum horizontal momentum flux is

$$\hat{M}_{D,max} = 0.25 g h_0^2 \ . \tag{2}$$

For greenwater events, we also measure the horizontal momentum flux of the flow on deck in our CFD simulations. A set of 'probes' are placed on the deck with which the horizontal momentum flux on deck at any instant, $M_{\mathrm{G,max}}$, can be obtained. Then the maximum momentum flux in both space and time, $\widehat{M}_{\mathrm{G,max}}$, is determined.

Schoenberg and Rainey [5] looked at the transient submergence of a shelf in still water using nonlinear potential flow. They highlighted the importance of overtopping duration, which may alter the momentum flux of on-deck flow away from that given by the dam-break solution. However, this "moving shelf" model still could not capture plunging-type behaviours during greenwater overtopping and did not retain the connection between freeboard exceedance and period which is imposed by waves.

We also consider duration, and use additional simplified simulations to enhance our understanding. For each overtopping simulation, we increase the original freeboard f to be high enough to prevent overtopping occurring and re-run the simulation. Then, by measuring the free surface elevation at the leading edge of the box, we can obtain the overtopping duration (the time duration when the wave elevation is above the original freeboard), $2T_{\mathrm{NOT}}$ and the 'imaginary' freeboard exceedance (i.e. the maximum wave elevation above the original freeboard), h_{NOT}, where NOT stands for no overtopping. This definition is consistent with most potential flow methods for determining freeboard exceedance which also assume that the deck is high enough to avoid overtopping. Further, h_{NOT} is perhaps less ambiguous than h_{OT} (h_{OT} stands for the freeboard exceedance measured with overtopping), because the maximum water level is always at the bow in the NOT case. An example showing the water profiles of disturbed incident waves at different time instants for both overtopping and no overtopping conditions is given in Fig.3. It can be seen that the increase of freeboard has little effect on the free surface in front of the box but increases the freeboard exceedance at the leading edge. A slight difference in overtopping duration exists near the runout phase.

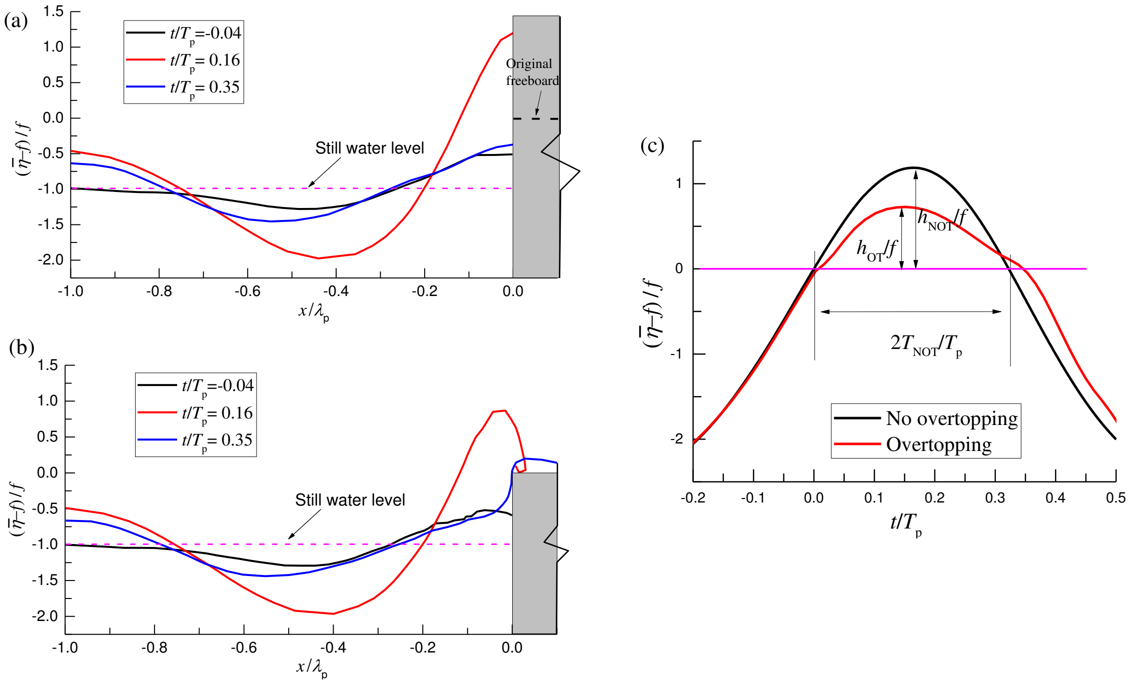

Fig.3 Free surface elevation for both overtopping and no overtopping conditions. λ_p/D=8, $A_{\mathrm{nl}}/\lambda_p$=0.03. (a) Water profiles at different time instants for no overtopping condition; (b) Water profiles for overtopping condition; (c) Surface elevation at the leading edge x=0 of the box.

In the following, we will explore the effect of overtopping duration on greenwater momentum flux directly. The first step is to normalize these physical properties using parameters from the no overtopping case. The classical dam break solution with h_0 replaced by h_{NOT} in Eq.(2) is used to normalize greenwater momentum flux. The overtopping duration T_{NOT} is normalized by $\sqrt{h_{\mathrm{NOT}}/g}$, which is the time scale of a dam-break with an initial height of h_{NOT}.

Fig.4 (a) gives the (contour line) variation of relative overtopping duration $T_{\mathrm{NOT}}/\sqrt{h_{\mathrm{NOT}}/g}$ with wave and box parameters. It should be noted that the box bottom exposed overtopping events (highlighted by the hollow symbol with "+" in the center) are discarded when calculating the contour lines. Both increase of wavelength (λ_p/D) and decrease of wave steepness ($A_{\mathrm{nl}}/\lambda_p$) will lead to an increase of the relative duration of overtopping, as expected.

As shown in Fig.4(b), the data of the normalized momentum flux versus the relative overtopping duration for the three different f/D ratios almost collapse onto a single curve. For smaller $T_{\mathrm{NOT}}/\sqrt{h_{\mathrm{NOT}}/g}$, the value of $\widehat{M}_{\mathrm{G,max}}/0.25gh_{\mathrm{NOT}}^2$ increases rapidly with the increase of $T_{\mathrm{NOT}}/\sqrt{h_{\mathrm{NOT}}/g}$. Then this rate becomes smaller for larger $T_{\mathrm{NOT}}/\sqrt{h_{\mathrm{NOT}}/g}$. The classical dam break solution over-predicts the momentum flux of greenwater at smaller overtopping duration (especially for HF type events) but gives an under-prediction at larger duration (for some PDB and DB events). It is noted that the overtopping types are not ordered by relative duration, and hence are not readily useful for predicting momentum flux.

The relative overtopping duration reveals that both the freeboard exceedance and overtopping duration are responsible for the greenwater momentum flux (or loading). The freeboard exceedance, h_{NOT}, calculated based on a no overtopping condition, may be used to get the momentum flux for the classical dam break (i.e. $0.25gh_{\mathrm{NOT}}^2$). Then the relative overtopping duration, which combines the effects of wave and ship parameters, can be used to give a simple prediction of the horizontal momentum flux (or damage potential) of greenwater events (i.e. to tell what fraction of the classical result applies). This dimensionless parameter may be used as a new measure for screening out the critical sea states associated with extreme greenwater events, improving the current industry practice focusing only on the freeboard exceedance.

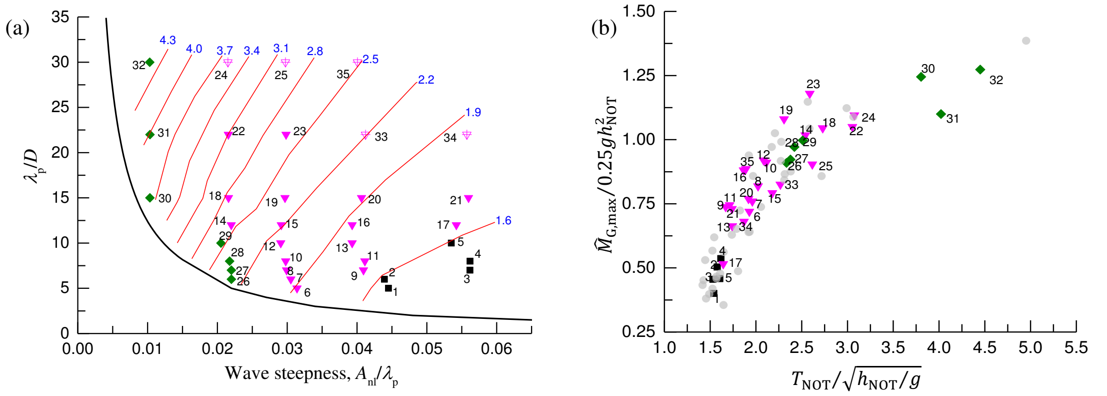

Fig.4 Variation of relative horizontal momentum flux with the relative overtopping duration for greenwater events. (a) The contour for the relative overtopping duration, *f*/*D*=0.25; (b) The maximum momentum flux, *f*/*D*=0.25. The light grey circular symbols represents the results for the other two *f*/*D* ratios.

6 Conclusions

NewWave type focused wave groups overtopping a 2D fixed rectangular box are numerically investigated using CFD. Consistent with existing experimental results, a range of overtopping events including dam-break (DB), plunging plus dam break (PDB) and hammer fist (HF) type have been identified and classified based on the incident wave steepness and the relative wave length. A key parameter – the relative overtopping duration – is proposed to combine the coupled effects of freeboard exceedance and overtopping duration on the maximum horizontal momentum flux (i.e. the damage potential) of shipped water flow on deck. Results indicate that the classical dam break solution over-predicts the momentum flux of greenwater at smaller values of the relative overtopping duration (especially for HF type events) while gives an under-prediction at larger duration (for some PDB and DB events). Further results will be presented at the workshop, including overtopping results for other *f*/*D* ratios, a modified dam break model to help interpret the results and an explanation for why the greenwater momentum flux is underestimated by the classical dam break solution for some cases. The conclusions drawn from this 2D study are currently being validated by experiments and 3D study.

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