*Abstract for 35th IWWWFB, Seoul National University, Korea - April 26-29, 2020*

# Experiments of wave-in-deck into a solid deck using focussed waves

H. Santo[1], P. H. Taylor[2], S. S. Dai[3], A. H. Day[3], E. S. Chan[1]

1: Technology Centre for Offshore and Marine, Singapore (TCOMS), Singapore
2: Faculty of Engineering and Mathematical Sciences, University of Western Australia, Australia
3: Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, United Kingdom
E-mail: harrif_santo@tcoms.sg

## 1 Introduction

Wave-induced fluid loading on space-frame structures such as offshore jackets and compliant towers has been thoroughly investigated by Santo et al. (2018b,a,c). The conclusion is that due to 'wave-current blockage' effects for statically-responding structures, and 'wave-current-structure blockage' effects for dynamically-responding structures, the effective hydrodynamic loads on the structures are reduced as compared to both the standard Morison equation Morison et al. (1950) as well as present industry guidelines, such as API API RP 2A (2000). Therefore, failures to bottom-founded structures can be attributed due to the exceedance of wave crests above design level (hence negative air gap), resulting in violent impact process termed 'wave-in-deck'.

Experimental studies on wave-in-deck or wave impact have been conducted in the past, see e.g. recent work by Mercier (2019); Ma and Swan (2020). Most of the studies make use of either regular or random waves in their simulations. We consider instead transient and non-periodic waves which are more representative of large waves on the open sea. The same set of focussed wave groups as used previously in Santo et al. (2018b,a) was simulated, and the impact force time histories on two deck models were measured. Similar use of focussed wave events were adopted in Yan et al. (2019); Ma and Swan (2020).

This paper aims to characterise the severe wave (impact) forces arising from wave-in-deck. Global forces are of interest, rather than point pressures, as the objective is to better assess the overall integrity of the overall structure when survivability is in question. Full details of this experimental work will be reported elsewhere soon.

## 2 Experimental setup

Experiments were conducted in a large towing tank in Kelvin Hydrodynamics Laboratory of University of Strathclyde, Glasgow. The tank is 76 m long, 4.6 m wide and 2.5 m deep. One end of the tank is equipped with Edinburgh Design 'flap-type' force-feedback wavemaker while the other end with passive wave absorption. A solid deck model with 1.05 m long, 0.40 m wide and 0.30 m deep was rigidly supported and suspended below a carriage which runs along the tank. The lowest natural frequency of the supporting system is $\sim$ 12 Hz. We consider inundation level of 1.5 and 4 cm. With 1:80 scaling ratio, 4 cm corresponds to 3.2 m at full-scale, which can be taken as $\sim$ 2 m from the bottom of the main beams of a typical North Sea platform with another $\sim$ 1 m into the deck level. At model-scale, this is modelled with a solid deck box with a square grillage of I-beams attached underneath the deck. The I-beams were 2.5 cm deep, the flanges are 9.5 mm wide and both the webs and flanges are 2.2 mm thick. Along the long axis of the deck, there are 8 beams in total running across the deck and 7 spaces between the beams. The first and last of these spaces are 14.5 cm wide, the central five spaces are 15.2 cm wide. Across the width of the deck there are 5 beams regularly spaced at 10 cm.

(a)

(b)

Figure 1: (a) Photograph of the overall setup and the towing tank. (b) Close-up view of the deck model which was rotated to 45° relative to the wave direction.

A piezoelectric type load cell (Kistler 9257B) with a natural frequency of $\sim 3.5$ kHz is mounted directly above the deck model. A resistance-based wave probe, sampled at the same rate as the force transducer and mounted from the towing carriage midway between the leading edge of the deck model and the side of the tank, was used to provide phase information of the incident waves. One orientation of the deck model was tested: head-on (which is $0°$), so the end-on dimensions of the model are 0.40 m wide by 0.30 m vertically.

A focussed wave group is used, based on a JONSWAP-based amplitude spectrum truncated at 1 Hz, with the frequency of the peak spectral energy at 0.52 Hz and a linear crest amplitude of 0.22 m at focus. The water depth was set at 1.8 m. Three different towing speeds, representing uniform in-line (or following) current at the model: 0, 0.14 and 0.28 m/s at model-scale (which corresponds to 0, 1.25 and 2.5 m/s at full-scale, respectively, assuming Froude scaling), so that for the model the horizontal fluid velocity in the wave crests adds to the current. A synchronisation system was set up to ensure that the deck model towed under different speeds meets the same wave group at the right place and at the right time.

# 3 Measured impact forces

Figure 2 presents a summary of horizontal and vertical wave-in-deck loads on (a) solid box with 1.5 cm inundation, (b) solid box with 4 cm inundation, and (c) solid box with I-beam gratings with 4 cm inundation. All are presented for three different towing (or current) speeds. Note that low-pass filtering at $\sim 32$ Hz is applied on forces from solid deck to remove the high frequency noise, however this is not applied on forces from solid deck with I-beam gratings.

Starting from the solid box without gratings, the horizontal impact force is characterised by a single large peak force followed by oscillations due to structural dynamics of the supporting system. There is clear dependency with levels of inundation as well as current speeds. The vertical force, on the other hand, has a large positive peak followed by downward negative (or suction) phase. For both inundation levels, there is a kink in the downward force due to the impact of the leeward of the focussed wave crest. It can be observed that the vertical force scales with different inundation levels but not with current speeds. Therefore, the suction phase of the vertical forces is not related to Bernoulli effects, but rather arises from vertical added mass effects, consistent with Baarholm (2009).

For the impact forces on a solid deck with I-beam gratings, the force structures look more complex and dominated by force spikes and high frequency oscillations. The occurrence of force spikes is due to the successive impingement of the wave crest on individual I-beams. For the same inundation, the peak forces are $3-4\times$ larger than for the case without gratings. Substantial air pockets entrapped in the I-beam gratings may play a role, consistent with the numerical observation by Chen et al. (2018). Computational Fluid Dynamics (CFD) is being used to provide more physical insight in parallel work, and the results will be reported in the near future.

We investigate the scaling of the horizontal impact loads with inundation levels and current speeds using a 'destruction of momentum' argument, i.e. assuming a perfect momentum transfer from the incident large wave crest into the impact on the vertical edge of the solid deck. Assuming the crest profile is linear in space, we can define $A = \cos(kx)$, where $A$ = linear crest height, $k$ = wavenumber, $d$ = inundation level, $2L$ = length of impact crest and $x$ = coordinate along wave propagation, with $x = 0$ centred at the leading vertical edge of the solid deck. From Figure 3, it can be deduced that $(A - d) = A\cos(kL)$, giving $(kL)^2 = 2d/A$, which can be derived from a local Taylor expansion. We also have $\omega T = kL$ where $\omega$ is wave frequency and $2T$ = duration of impact.

The volume of the undisturbed wave crest that impacts on the deck, so above a level of $(A-d)$, is then obtained by integrating $B \times A[\cos(kx) - \cos(kL)]dx$ over a horizontal distance of $2L$, with $B$ = lateral width of the box across the tank. This yields $\mathit{V\!\!\!/} = B(A/3)(2d/A)^{3/2}(g/\omega^2)$, where the deepwater dispersion equation has been used. Note that we take $\omega \sim 2\pi/T_z$, where $T_z$ is the mean zero-crossing wave period.

The horizontal momentum, defined as a product of mass and velocity, can be expressed as:

$$\begin{aligned} M_h &= \rho \mathit{V\!\!\!/} \times u_{max} \\ M_h &= \rho(B/3)A(2d/A)^{3/2}(g/\omega^2) \times u_{max} \end{aligned} \tag{1}$$

with $u_{max}$ being the horizontal velocity of water particle at the crest and assumed uniform over depth of inundation. For non-breaking waves, $u_{max} = \omega A$. Dividing the horizontal momentum, $M_h$, by the impact duration ($2T$), yields the estimated horizontal impact force, expressed as:

$$\begin{aligned} F_h &= \frac{M_h}{2T} = \frac{\rho(B/3)A(2d/A)^{3/2}(g/\omega^2) \times u_{max}}{(2d/A)^{1/2}(1/\omega)} \\ F_h &= \frac{2}{3}\rho d B \frac{\omega}{k} \times u_{max} \end{aligned} \tag{2}$$

Note that, to a first approximation, in-line current will add in linearly into the wave kinematics, $u_{max}$, and then linearly into the force and the horizontal impulse, likewise for inundation level. To a second approximation, the duration of impact will shorten slightly.

How well the analytical approximation works can be assessed from Figure 4, where all the measured horizontal forces have been normalised by Equation 2. It can be seen that all the peaks are now approximately collapsed,

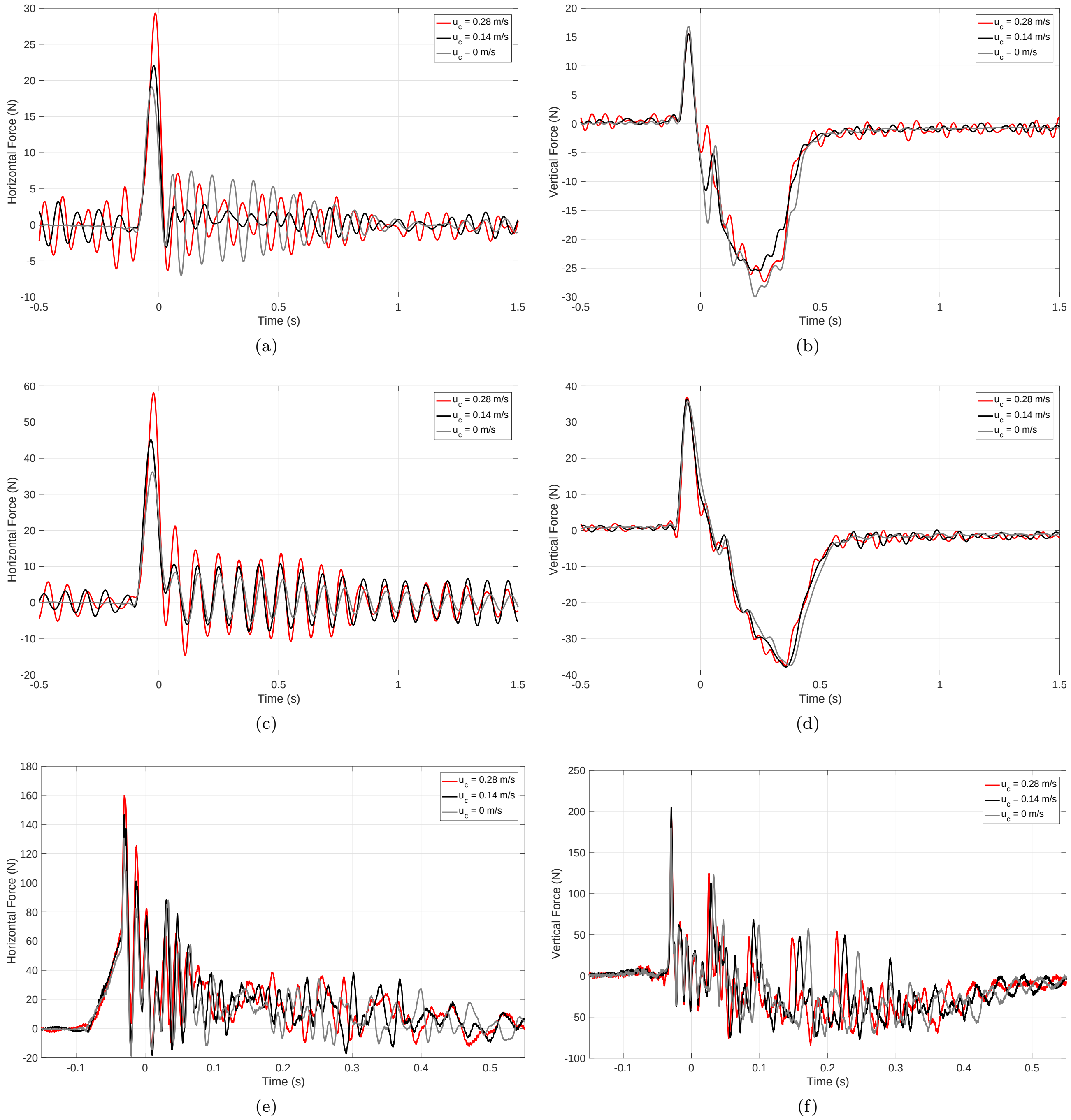



Figure 2: Measured force time histories for solid deck with (a,b) 1.5 cm inundation and (c,d) 4 cm inundation, and for (e,f) solid deck with I-beam gratings with 4 cm inundation, all for three different current speeds. All results are averaged over 5 repeated tests.

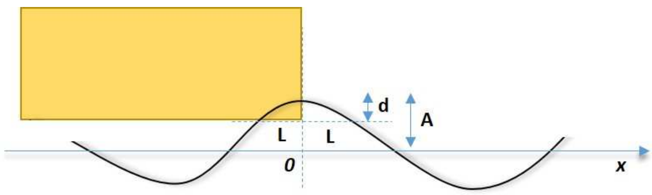
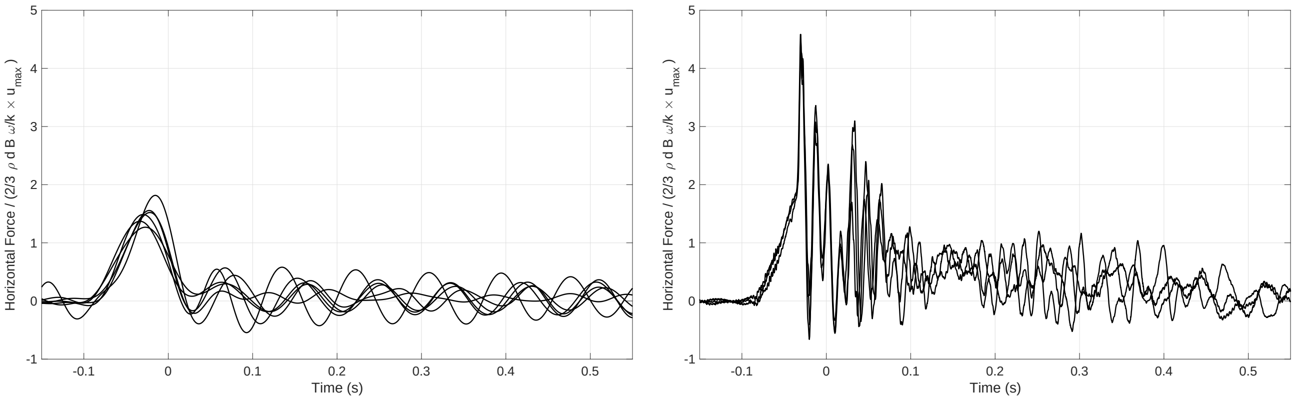



Figure 3: Schematic diagram of the set-up in side view.

which provide some support to the scaling argument where both the inundation and the in-line current will add in linearly into the wave impact forces to a first order approximation.

# 4 Conclusion

Wave-in-deck experiments were conducted in a carefully-controlled environment using a combination of a single focussed wave and towing carriage motion incident on to a solid deck without and with I-beam gratings. In total,




(a) (b)

Figure 4: Normalised measured horizontal force time histories for solid deck (a) with 1.5 and 4 cm inundation levels and (b) with I-beam gratings with 4 cm inundation, all for three different current speeds.

two different levels of inundation and three different towing speeds were considered. The measured horizontal and vertical forces are described, of which the loads for the deck with I-beam gratings show more complex structure and much larger force spikes due to wave impingement on some of the individual I-beams and possible entrapped air effects. To investigate how the horizontal peak force scales with inundation levels and currents, a simple analytical model is proposed, which predicts linear scaling with current and inundation level. The measured horizontal impact forces are normalised according to the analytical model, and in general, there is a good collapse in the peak impact forces during the impact duration.

# Acknowledgements

We acknowledge the support from Singapore Maritime Institute (SMI) through project ID SMI-2015-OF-12 to National University of Singapore where the earlier part of the work was conducted, and A*STAR Science and Engineering Research Council through grant number 172 19 00089 under the Marine & Offshore Strategic Research Programme (M&O SRP) to TCOMS where the latter part of the work was completed. The technicians at Kelvin Hydrodynamics Laboratory provided a high quality facility and technical service.

# References

API RP 2A, 2000. Recommended practice for planning, designing, and constructing fixed offshore platforms–working stress design. API RP2A-WSD 21st Edition with Erratas and Supplements 1, 130–132.

Baarholm, R., 2009. Experimental and theoretical study of three-dimensional effects on vertical wave-in-deck forces. In: ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers Digital Collection, pp. 451–459.

Chen, Y., Wu, Y., Bahuguni, A., Gullman-Strand, J., Lv, X., Lou, J., Ren, W., 2018. Directional wave-in-deck loading on offshore structures with porous and plated decks with supporting I-beams. Coastal Engineering 137, 79–91.

Ma, L., Swan, C., 2020. An experimental study of wave-in-deck loading and its dependence on the properties of the incident waves. Journal of Fluids and Structures 92, 102784.

Mercier, R., 2019. Review of experimental modeling of green water in laboratories. In: The 29th International Ocean and Polar Engineering Conference. International Society of Offshore and Polar Engineers, ISOPE-I-19-137.

Morison, J. R., O'Brien, M. P., Johnson, J. W., Schaaf, S. A., 1950. The force exerted by surface waves on piles. Journal of Petroleum Technology 2 (5), 149–154.

Santo, H., Taylor, P. H., Day, A. H., Nixon, E., Choo, Y. S., 2018a. Blockage and relative velocity Morison forces on a dynamically-responding jacket in large waves and current. Journal of Fluids and Structures 81, 161–178.

Santo, H., Taylor, P. H., Day, A. H., Nixon, E., Choo, Y. S., 2018b. Current blockage and extreme forces on a jacket model in focussed wave groups with current. Journal of Fluids and Structures 78, 24–35.

Santo, H., Taylor, P. H., Day, A. H., Nixon, E., Choo, Y. S., 2018c. Wave-current blockage: reduced forces for the re-assessment of ageing space-frame offshore structures. In: Offshore Technology Conference, OTC 29036.

Yan, B., Luo, M., Bai, W., 2019. An experimental and numerical study of plunging wave impact on a box-shape structure. Marine Structures 66, 272–287.