LARGE-SCALE AND SMALL-SCALE EFFECTS IN WAVE BREAKING INTERACTION ON VERTICAL WALL ATTACHED WITH LARGE RECURVE PARAPET

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Two sets of experiments on the vertical wall attached with recurve parapets performed at 1:1 and 1:8 scale are compared to study the influence of scale, model and laboratory effects. The small-scale (1:8) experiment scaled to large-scale (1:1) using Froude scaling, and Cuomo et al. (2010) method are compared. Comparing both the methods for scaling impact pressure, Cuomo et al. (2010) predicts well in the impact zone, whereas Froude scaling is better in the up-rushing zone. In estimating integrated impact force, Froude scaling method over-estimates compared to Cuomo et al. (2010). Overall, Cuomo et al. (2010) work better for scaling up impact pressure and forces compared to Froude scaling method. These preliminary observations are based on one type of recurved parapets only.

Keywords: Scale effects, recurve parapet, wave impact, large-scale

INTRODUCTION

The wave impact pressure and forces are the critical parameters for the design of coastal structures. Most of the empirical formula derived is based on the model scale experiments modelled using Froude scaling law. Unfortunately, the Froude law does not encounter for the air entrapment, so comparing breaking impact from field and model scale using length ratio will yield erroneous results. Later, Cuomo et al. (2010), presented a method to scale the impact pressure from model tests to prototype by using correction factors for the Froude scaling law and compared it with large-scale results using different test conditions data sets. The present paper intends to provide insights on the parameters like impact pressure and forces due to scale effects measured in a vertical wall attached with large recurve parapets carried out for identical test conditions.

Based on existing works of literature, the difference between the up-scaled model and prototype occur due to the following effects, which are sub-grouped into model and laboratory effects, scale effects and non-repeatability effects. In model and laboratory effects (Yalin 1971, Ivicsics 1978, Bretschneider, in Kobus 1980, Novak 1984, Hughes1993), the differences created due to wave generation, type of water used for testing, materials used for model construction, choice of instruments used and their fixed positions, measurement effects (Schuttrumpf and Oumeraci 2005) need to be considered. In scale effects (Yalin 1971, Le Me´haute´ 1990, Hughes 1993, Martin and Pohl 2000, Heller 2007), Scaling law, compressibility, surface tension, viscosity, water properties are included. In non-repeatability effects (Streicher et al. 2019): 3D effects of turbulent bore front, Air entrainment, Air entrapment – Cushioning effect (Bullock et al. 2007) need to be considered. In this study, only model and laboratory effects and scale effects are discussed.

EXPERIMENTAL MODELLING

The quasi-prototype scale 1:1 experiments are carried out at Large Wave Flume (Großer Wellenkanal, G.W.K.) of Forschungszentrum Küste (F.Z.K.) in Hannover, Germany (Ravindar et al., 2017) and model scale 1:8 experiments are performed at shallow wave flume at Department of Ocean Engineering, Indian Institute of Technology, Madras, India (Ravindar et al., 2021) are shown in Figure 1. The flume has a flat bottom and an approaching slope of 1:10 that ends at the toe of a sea wall. The curve-shaped parapets are mounted on a vertical wall. In total, three different parapets are tested based on the angle of extension (α_e) for different wave breaking conditions, namely slightly breaking, breaking with small air trap and breaking with large air trap. In this paper, only large recurve parapet results are considered.

The instrumentations used in the prototype are 16 pressure transducers sampled at 5000 Hz; 8 nos. are fixed at the vertical sea wall, and eight numbers are fixed on the curved parapet, 12 wave gauges

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sampled at 100 Hz along with two video cameras are shown in Figure 2a. Tests are carried out for regular waves with a constant water depth of 4.1 m for wave period 4s to 8s and for wave heights 0.5m to 0.8m. Similarly, in model scale, seven pressure transducers sampled at 9600 Hz; 4 no. at the vertical wall and three nos. in the curved parapet, six wave gauges sampled at 100 Hz and with three cameras are shown in Figure 2b. These two experiments were carried out for the same wave characteristics, leading to the same kind of breaking wave phenomenon in large and small-scale. The key is modelling the air entrapment, which influences the pressure and force. Hence, based on these experiments, it is intended to infer the difference and compare it with the Bagnold-Mitsuyasu compression law.

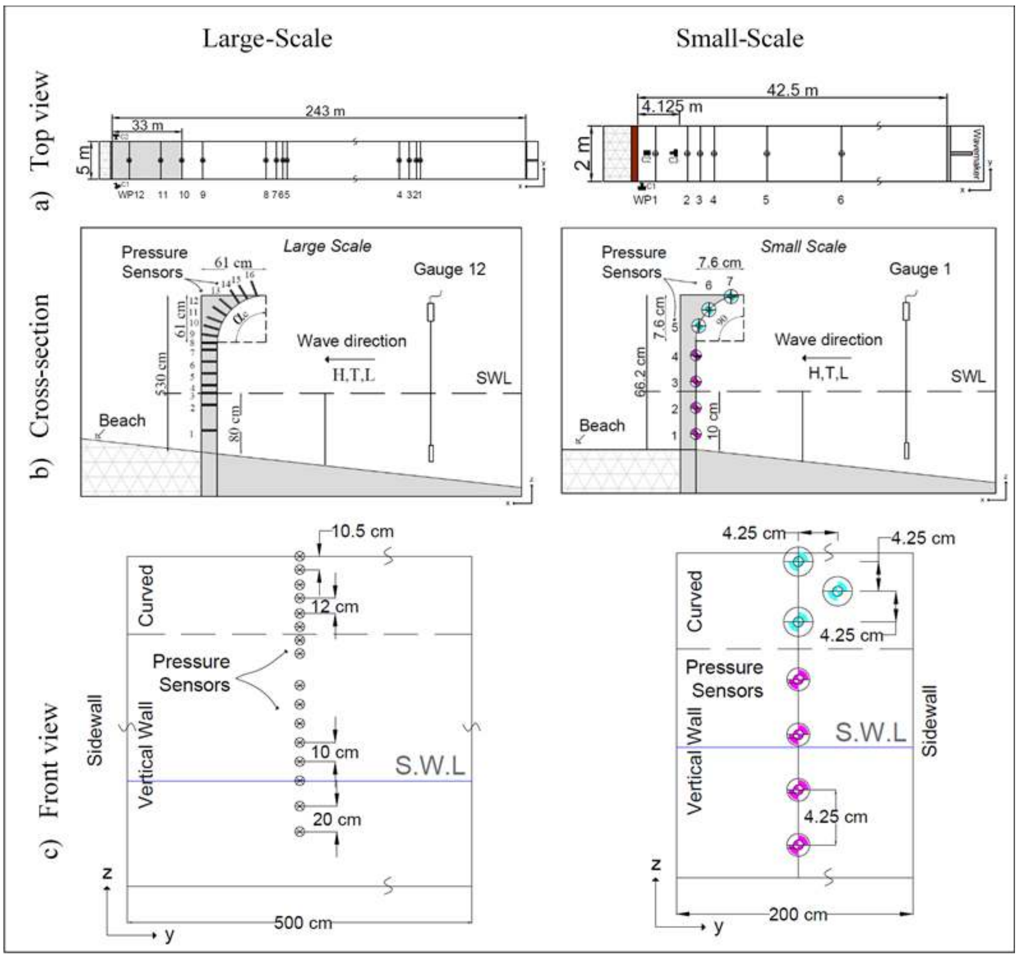


Figure 1. Top view (a), Cross-section (b) and Front view (c) of flume and structure in Large-scale and small-scale.

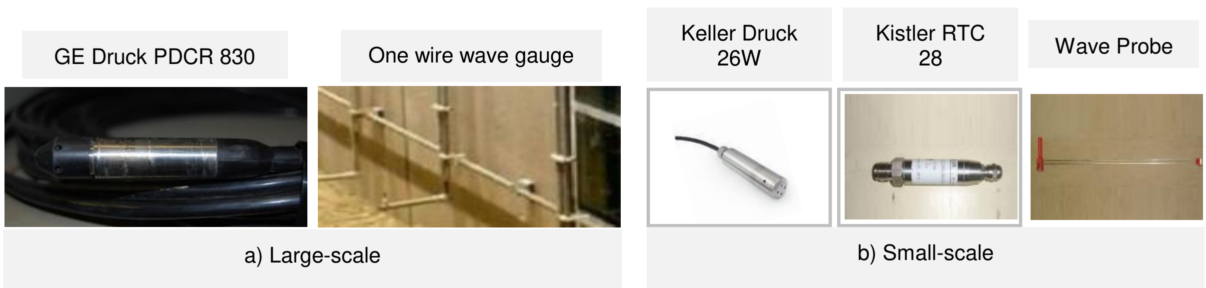


Figure 2. Large-scale (a) and Small-scale (b) instrumentations for measuring pressure and wave elevation.

The tests were conducted for monochromatic waves with constant water depth for the following combinations, as shown in Table 1. The incident wave height is limited between 0.5m to 0.8m because less than that did not create sufficient impact and greater than 0.8m created higher load exceeding safety conditions. Similarly, wave period less than 4s caused standing wave formation and greater than 8s created high loads. In small-scale, the cases corresponding to large-scale are only discussed in this paper. In small-scale, wave steepness is maintained as close as possible to large-scale.

Table 1: Description of tests considered in this study

	Large-scale			Small-scale		
ID	H_i (m)	T (s)	H_i/L	H_i (m)	T (s)	H_i/L
H05T8	0.5	8	0.010	0.0625	2.8	0.010
H06T6	0.6	6	0.017	0.075	2.1	0.017
H06T8	0.6	8	0.012	0.075	2.8	0.012
H07T4	0.7	4	0.033	0.0875	1.4	0.034
H07T6	0.7	6	0.020	0.0875	2.1	0.020
H07T8	0.7	8	0.014	0.0875	2.8	0.015

SCALE EFFECTS CRITERIA

The critical limits for scale effects are given in Le Méhauté (1976) and Heller (2011). For Froude based models, Reynolds number and Weber number should be greater than the limiting values as shown in Table 2 provided by Schüttrumpf, (2001). Based on Führböter, 1986, parameters affecting wave breaking are shown in Figure 3. As per Figure 3, wave propagation depends on Froude number and wave breaking depends on Weber, Reynolds and Cauchy number. For wave propagation, the practical limits derived by Le Méhauté are water depth, d should be greater than 2.0cm (Le Méhauté, 1976). Linear wave propagation is affected less than 1% by surface tension if wave period, T is greater than 0.35 s (corresponding to wavelength, L > 0.17 m, Hughes 1993). Similarly, for wave breaking, the effect of surface tension is negligible for Weber number greater than 10. Free surface water flows should be greater than 5 cm to avoid significant surface tension scale effects (e.g. Heller et al. 2005).

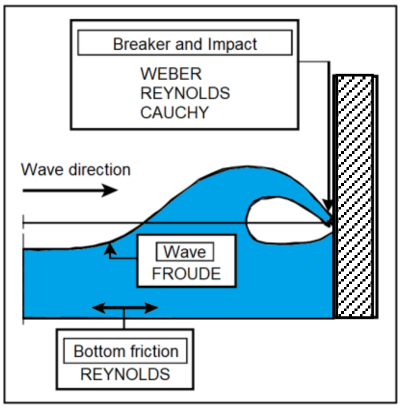


Figure 3. Parameters affecting wave breaking modified from Führböter, 1986.

Table 2: Critical limits for scale effects (Schüttrumpf, 2001)

Process	Relevant forces	Similitude law	Critical limits
Wave Propagation	Gravity force Friction forces Surface tension	Fr_W, Re_W, W_e	$Re_W > Re_{W,crit} = 1.10^4$ T>0.35s; d>2.0 cm
Wave breaking	Gravity force Friction forces Surface tension	Fr_W, Re_W, W_e	$Re_W > Re_{W,crit} = 1.10^4$ T>0.35s; d>2.0 cm

As the critical limits shown in Table 2 are satisfied in the study, the small-scale experiment is free from scale effects from wave propagation and breaking due to governing models like Froude, Weber, Reynolds and Cauchy.

FROUDE SCALING

As the study is focused on the free surface flow of gravity waves and gravitational acceleration being the dominant physical parameter. Froude's law of similitude is applied to scale the small scale model results. Using Froude scaling factors shown in Table 3, the wave elevation, pressure and force are compared between the scaled model (1:8) and large-scale (1:1) and distinguish the differences in trend and magnitude.

Table 3: Froude scaling factors

Parameter	Froude scaling factor
Length [m]	λ
Time [s]	√ λ
Pressure [kN/m^2]	λ
Force [kN]	λ^2

RESULTS AND DISCUSSION

Wave elevation and amplitude spectrum from two scales:

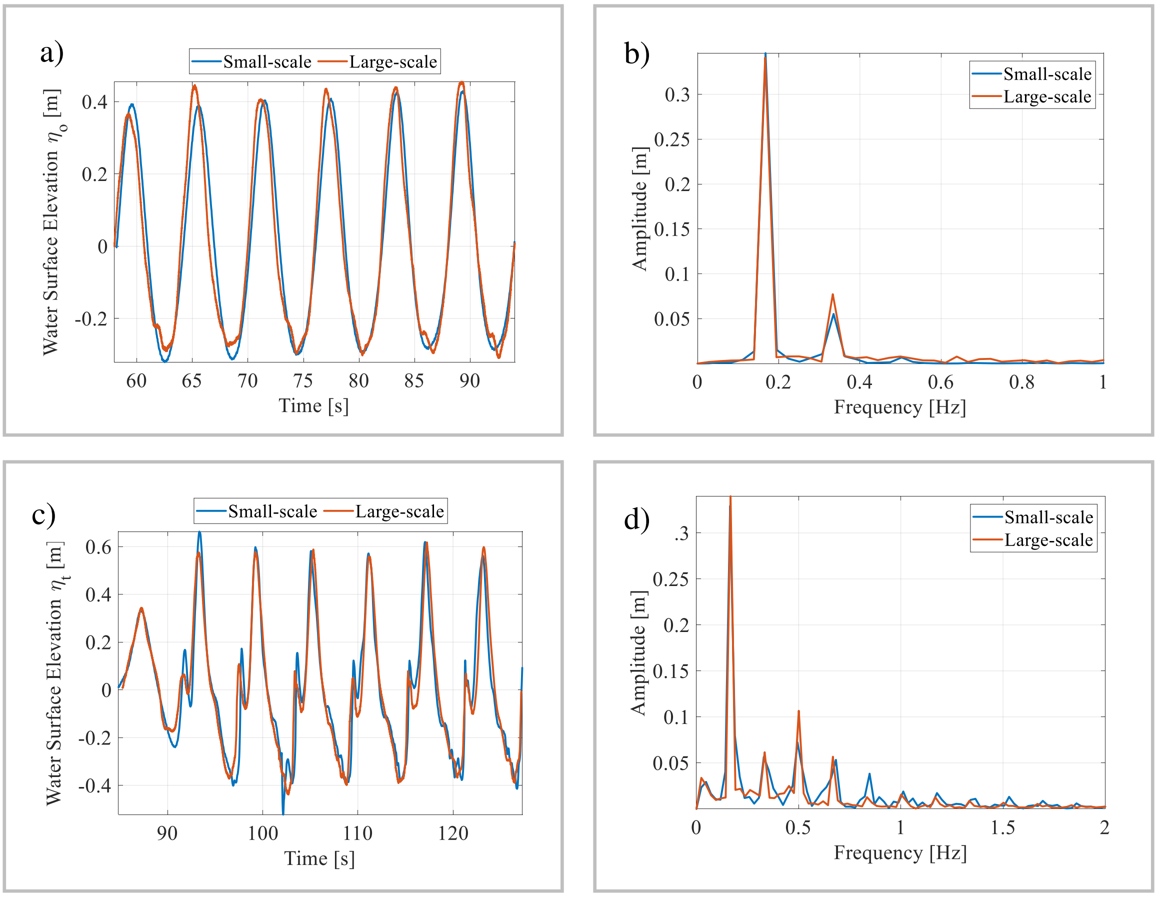


Figure 4. Wave elevation and amplitude spectrum for H07T6 case, the blue line indicates the up-scaled model and red line indicates prototype.

Figure 4 shows the comparison of wave elevation and amplitude spectrum between small-scale (in blue line) and large-scale (in red line) for the H07T6 test case. In agreeing with the theory, Froude scaling provides a good agreement between small-scale and large-scale experiment. The ratio of energy at toe and incident location (E_t/E_i) for H07T6 case is 1.32. Similarly, the ratio for all case is shown in the below table. The highest difference is found in the cases of H06T6 and H07T6, which comes under the breaking air with small air trap category. The difference is contributed by model and laboratory effects such as slope recreation, maintaining water depth and type of wave generated. In large-scale modified trochoidal wave, the theory is used, whereas in small-scale Stroke second-order theory is used.

Table 4: Energy ratio at toe and incident location (Et/Ei) for all test cases

ID	H/L	Small-scale	Large-scale	SmallScale/LargeScale
		E_t/E_i	E_t/E_i	
H05T8	0.0103	0.4016	0.3500	1.1475
H06T6	0.0171	2.8425	2.1900	1.2982
H06T8	0.0124	2.9906	2.8950	1.0331
H07T4	0.0333	2.0848	1.9246	1.0833
H07T6	0.0199	2.7218	2.0580	1.3228
H07T8	0.0144	2.9421	2.6670	1.1033

The difference in energy dissipation between scaled model and large-scale is in the range of 3-32 %. Even though small scale results are overestimated, Froude scaling works perfectly well; this proves the credibility of the model experiment in recreating the large-scale conditions.

Comparison of pressure & force using Froude Scaling:

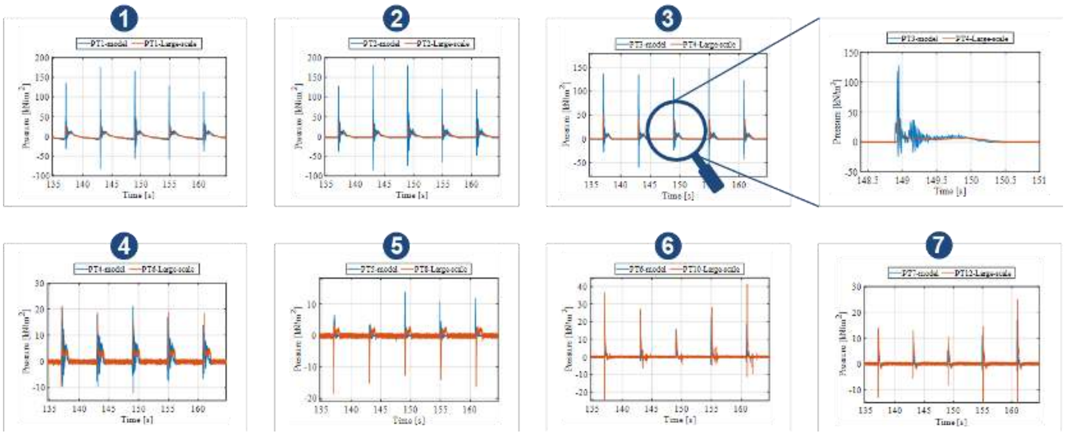


Figure 5. Pressure time history variation for all seven pressure probes in model and corresponding pressure probes in prototype and a zoomed version of the PT3 model alone using Froude scaling for the H07T6 test case.

Figure 5 shows one to one comparison of impact pressure from small-scale (blue line) and large-scale (red line) for the H07T6 test case. The pressure transducer from small-scale is compared with the closest one in large-scale. Due to space constrain in small-scale, the size of the pressure transducer and curvature effect, the pressure transducer in recurve could not be placed at the exact location. Based on Figure 5, the pressure-time history of 1 to 3 have overestimated pressure magnitude in small-scale compared to large-scale. There is good agreement in trend and magnitude in 4, 6 and 7. There is a poor agreement in location 5; this is due to space restriction in small-scale where the pressure transducer could not be placed at the exact location as in large-scale. Froude scaling over-predicts the pressure near impact location and compared well in other locations.

Similarly, impact force calculated from the integration of pressure transducers, 16 nos. in large-scale and seven nos. in small-scale are shown in Figure 6. It is clear that Froude scaling method over-estimates the impact force, the ratio of energy between small-scale and large-scale is 1.7519.

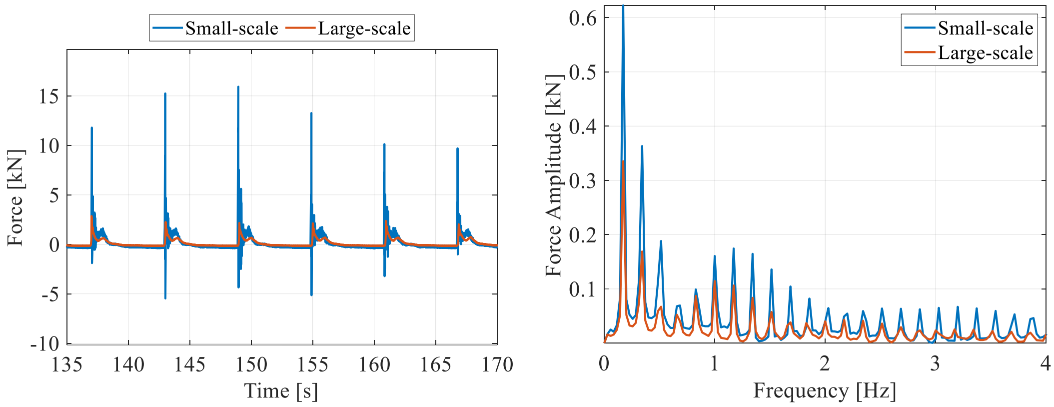


Figure 6. Force time history and spectrum from integrated pressure from the H07T6 test case. In the model scale (7 pressure transducers) and prototype (16 pressure transducers) are considered using Froude scaling method.

Table 5 shows the ratio between Froude upscaled small-scale and large scale for parameters like maximum pressure in kPa for location 3 based on Figure 5 and impact force. Location 3 is selected because it is closer to still water level. From table 5, it is clear that the Froude scaling over-estimates the pressure and forces all cases. The difference range is lesser in H05T8 (non-breaking case) and H07T4 (slight breaking case).

Table 5: Maximum pressure and force for the up-scaled model using Froude scaling and prototype

Test ID	Maximum pressure (kPa) for location 3			The maximum force (kN)		
	Froude Up-scaled model	Prototype	(Model-Prototype)/ Prototype	Froude Up-scaled model	Prototype	(Model-Prototype)/ Prototype
H05T8	10.74	9.45	0.14	2.43	0.56	3.38
H06T6	111.23	47.52	1.34	12.63	0.99	11.71
H06T8	78.62	26.29	1.99	8.51	1.25	5.82
H07T4	39.85	21.88	0.82	3.65	1.13	2.24
H07T6	146.31	50.86	1.88	15.82	2.76	4.73
H07T8	64.09	27.65	1.32	8.68	3.39	1.56

Comparison of pressure & force using Cuomo et al. (2010):

The parameters from experiments in two different scale are processed using modified Froude law proposed in Cuomo et al. (2010). Initially, parameters like u_0, D and k_w are calculated for model and prototype based on the geometrical characteristics using equations 1 to 3. Then, Bagnold number (Bgn) for model and prototype are computed using equation 4. Based on the scale factor discussed in Cuomo et al. (2010), the scale factor is obtained using equation 5. The scale factor is applied to impact pressure from model to upscale it to a large scale. The parameters obtained for the H07T6 test case are shown in Table 6.

$$u_0 = \sqrt{g(d + H_{m0})} \quad (1)$$

$$D = \pi / 12 \cdot H_{m0} \quad (2)$$

$$k_w = 0.2 \cdot (1 - \pi / 12) \cdot H_{m0} \quad (3)$$

$$Bgn = \frac{\rho_w \cdot k_w \cdot u_0^2}{p_0 \cdot D} \quad (4)$$

$$\lambda_s = \frac{(p_{max,P} - p_0) / p_0}{(p_{max,M} - p_0) / p_0} \quad (5)$$

Table 6: Parameter calculated using Cuomo et al. (2010) for H07T6 case

Test ID	Unit	Model	Prototype
H_{m0}	m	0.0875	0.7
T_m	s	2.1	6
d	m	0.1	0.8
u_0	m/s	1.3562	3.8360
k_w	m	0.0129	0.1033
D	m	0.0229	0.1833
Bgn	-	0.0102	0.0819
$(p_{max}-p_0)/p_0$	-	0.1287	0.4154

In analogy to Froude scaling section, the comparison of impact pressure scaled using Cuomo et al. (2010) method and large scale is shown for all location in small-scale for H07T6 case in Figure 7. Among that, the pressure-time history of 1 to 3, which are placed in vertical part has a good agreement in pressure magnitude. In recurve parapet, the pressure magnitude is under-estimated in 4, 6 and 7. This mismatch infers that Cuomo scaling works better only near the impact zone for which it was proposed.

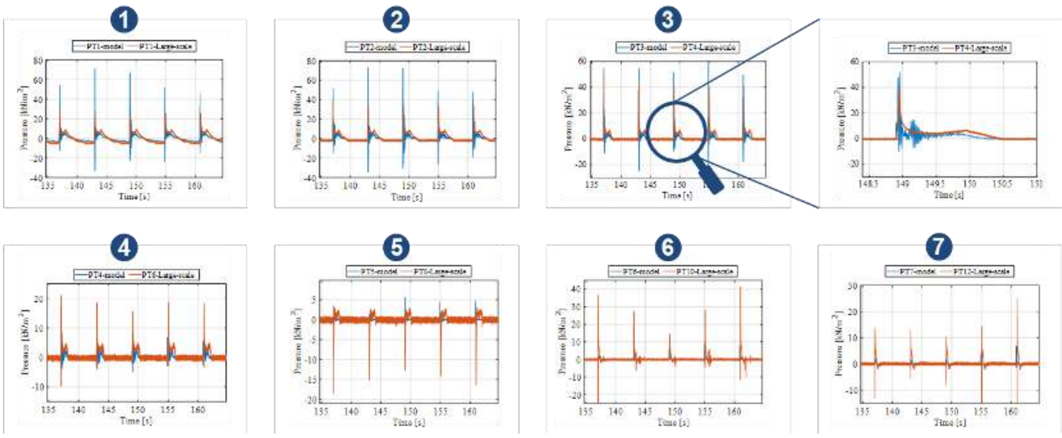


Figure 7. Pressure time history variation for all seven pressure probes in model and corresponding pressure probes in prototype and a zoomed version of the PT3 model alone using Cuomo et al. (2010) method for the H07T6 test case.

Similarly, in Figure 8, force calculated from small-scale impact pressure scaled using Cuomo et al. (2010) and large scale are shown. The comparison is better than Froude scaling from Figure 6. The energy ratio between small-scale and large-scale from the force amplitude spectrum is 0.7054.

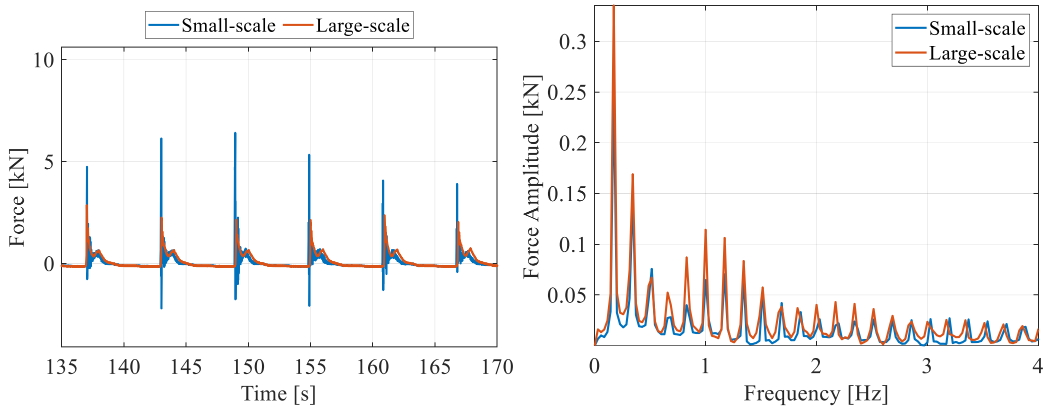


Figure 8. Force time history and spectrum from integrated pressure from the H07T6 test case. In the model scale (7 pressure transducer) and prototype (16 pressure transducer are considered) using Cuomo et al. (2010) method.

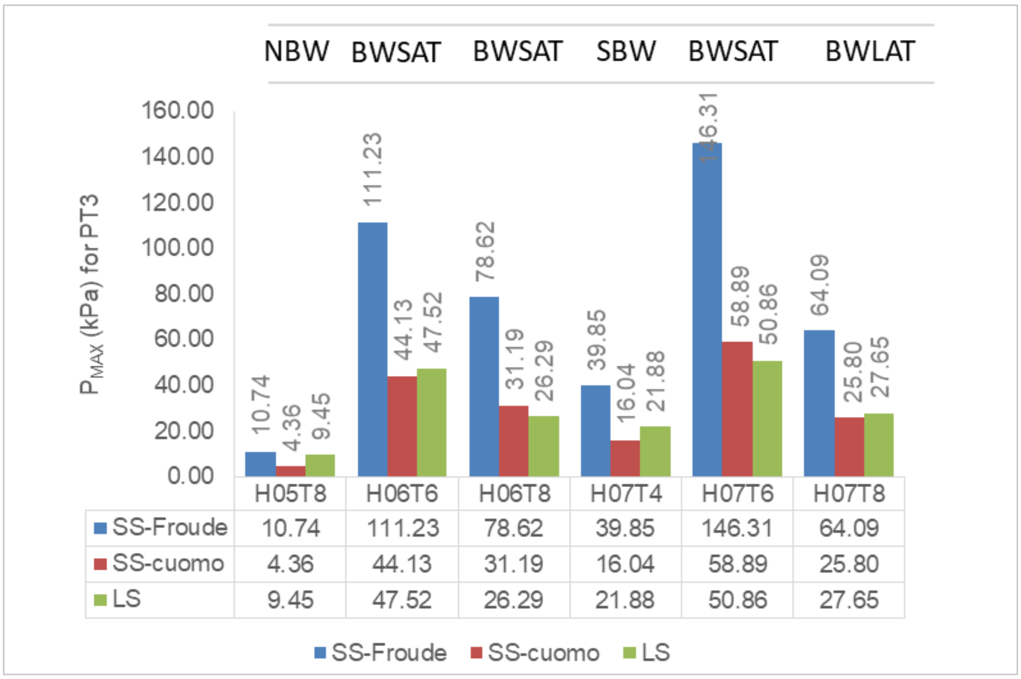
Table 7 shows average pressure and force for the up-scaled model using Cuomo et al. (2010) scaling and prototype. The Cuomo et al. (2010) scaling method compares well than Froude scaling in both pressure and forces. The pressure difference is lesser compared to the force, and this is because the number of transducers considered for integration is different in large-scale and small-scale. The maximum differences in force are found in H06T8 and H07T6 cases, which comes under a breaking wave with small air trap category.

Table 7: Maximum pressure and force for the up-scaled model using Cuomo et al. (2010) and prototype

Test ID	Maximum pressure (kPa) for location 3			The maximum force (kN)		
	Cuomo Up-scaled	Prototype	(Model-Prototype)/ Prototype	Cuomo Up-scaled	Prototype	(Model-Prototype)/prototype
H05T8	4.36	9.45	-0.54	0.99	0.56	0.78
H06T6	44.13	47.52	-0.07	5.01	0.99	4.04
H06T8	31.19	26.29	0.19	3.38	1.25	1.71
H07T4	16.04	21.88	-0.27	1.47	1.13	0.31
H07T6	58.89	50.86	0.16	6.37	2.76	1.30
H07T8	25.80	27.65	-0.07	3.49	3.39	0.03

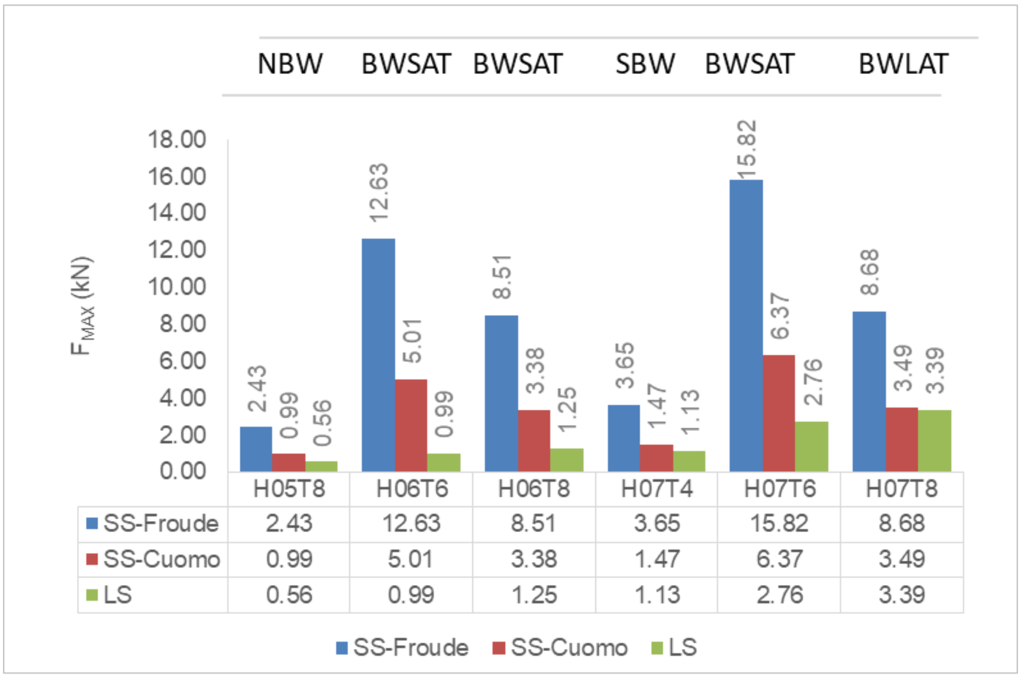
Comparison of pressure & force between Froude scaling and Cuomo et al. (2010):

Figure 9 and 10 show the comparison of maximum pressure (location 3) and force from small-scale study scaled using Froude and Cuomo et al. (2010) method and large-scale. In this figure, all the breaking classifications (as discussed in Ravinder et al., 2019) are shown. Except in the case of H05T8 in pressure, Cuomo et al. (2010) method perform better in predicting pressure and force scaled from small-scale to large scale studies.



	H05T8	H06T6	H06T8	H07T4	H07T6	H07T8
SS-Froude	10.74	111.23	78.62	39.85	146.31	64.09
SS-cuomo	4.36	44.13	31.19	16.04	58.89	25.80
LS	9.45	47.52	26.29	21.88	50.86	27.65

Figure 9. Comparison of maximum pressure at location 3 for Froude up-scaled small-scale, Cuomo et al. (2010) upscaled small-scale and prototype.



	H05T8	H06T6	H06T8	H07T4	H07T6	H07T8
SS-Froude	2.43	12.63	8.51	3.65	15.82	8.68
SS-Cuomo	0.99	5.01	3.38	1.47	6.37	3.49
LS	0.56	0.99	1.25	1.13	2.76	3.39

Figure 10. Comparison of maximum force for Froude up-scaled small-scale, Cuomo et al. (2010) upscaled small-scale and prototype.

Table 8: Differences in pressure and force for the up-scaled model using Froude and Cuomo et al. (2010) method and prototype

Test ID	**Difference for P_{max} for PT3 w.r.t Large-scale**		**Difference for F_{max} w.r.t Large-scale**	
	Small-scale -Froude	Small-scale-Cuomo	Small-scale -Froude	Small-scale-Cuomo
H05T8	**0.14**	-0.54	3.38	**0.78**
H06T6	1.34	**-0.07**	11.71	**4.04**
H06T8	1.99	**0.19**	5.82	**1.71**
H07T4	0.82	**-0.27**	2.24	**0.31**
H07T6	1.88	**0.16**	4.73	**1.30**
H07T8	1.32	**-0.07**	1.56	**0.03**

CONCLUSION

The paper presents the preliminary investigation on scaling the small-scale pressure/force impacts studies to large scale or prototype, by carrying out identical tests as close as possible. The small-scale results are initially verified by comparing the measured wave time histories. Based on Froude scaling, the difference in energy dissipation is in the range of 3-32 % for the generated waves. The difference is contributed by model effects such as reproduction of slope, maintaining water depth and type of wave generated. Froude scaling has a good agreement in the up-rushing zone but overestimates the pressure near the impact zone. Cuomo et al. (2010) have good agreement in the impact zone but underestimates the pressure other than impact zone. Force calculated by integrating pressure is over predicted in Froude scaling method compared to Cuomo et al. (2010). The force difference is higher in breaking cases with small air trap (BWSAT) compared to other breaking scenarios. Overall, Cuomo et al. (2010) work better for scaling up impact pressure and forces compared to Froude scaling method. This observation is for large recurve parapet type with the six identical test conditions carried out in small and large scales. Further results with different parapet types for a more significant number of waves will be investigated in future.

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