THE INCREASE IN WAVE WAKE CHARACTERISTICS OF MARINE VESSELS WHEN ACCELERATING

Gregor Macfarlane, Keegan Graham-Parker, Michael Connellan
Australian Maritime College, University of Tasmania
Launceston, Tasmania, Australia

ABSTRACT

The waves generated by ships and boats (often referred to as wake wash, wave wake or simply wash) have been known to result in the erosion of riverbanks, damage to maritime structures, or be hazardous to other users of the waterway. The vast majority of research in this field to date has focused on the characteristics of these waves when the vessel is travelling at constant forward speed. Recent work by the authors has identified significant transient effects that occur while a vessel accelerates up to the desired operational speed, where both the height and period of the maximum wave generated are significantly greater than those generated at the corresponding steady-state speed. This notable increase in wave energy can be important, particularly where vessels are required to accelerate on a regular basis when operating in sheltered waterways with limited water depth. Common examples are commuter ferries that make regular passages between passenger terminals and hence pass through the trans-critical speed zone to operate at super-critical speeds (in terms of depth Froude number).

In this paper, a study into these transient effects through physical scale-model experimentation is expanded to include different hull forms, including a typical "low wash" catamaran river ferry and a prismatic monohull. Results indicate that the increase in height of the maximum wave can exceed 80% and the period of this wave increase by more than 30% as a result of the acceleration phase compared to the steady-state speed. This poses the question whether these transient effects should form part of the assessment process when considering whether a vessel meets criteria imposed to regulate wash impacts.

The same model scale data is also used to advise the model test community the required distance for a ship model to achieve a steady-state following the acceleration phase during model scale tests in facilities such as towing tanks or basins.

Keywords: Wave wake; wash; acceleration, depth Froude number; ferry operations; monohull; catamaran, experiments.

NOMENCLATURE

Fr_h	depth Froude number
h	water depth (m)
H_m	height of the maximum wave (m)
L	length of the vessel / ship model (m)
$L/\nabla^{1/3}$	slenderness ratio
T_m	period of the maximum wave (s)
u	ship model velocity (m/s)
x	longitudinal distance from start position (m)
∇	displaced volume (m^3)

INTRODUCTION

Recent work by Macfarlane and Graham-Parker [1] investigated the effect on the magnitude of the waves generated by a marine vessel as it accelerates or decelerates its speed. Prior to this work, the vast majority of studies into the waves generated by ships and boats had only considered the characteristics of the waves when the vessel travels at constant forward speed. However, it is not unusual for commuter ferry operations that make regular passages between passenger terminals/wharves to frequently accelerate and decelerate between a stationary position and the desired operational speed.

It is also becoming increasingly common for these ferry services to operate at high speed on waterways that possess sensitive shorelines that are susceptible to erosion due to wave impacts. In these cases, the water depth is often considered shallow in terms of depth Froude number, meaning that waves with longer periods may be generated, hence containing greater energy and potentially be more damaging to surrounding shorelines [2, 3]. Thus, knowledge about any transient effects that occur during the acceleration phase may be of interest, particularly to bodies that are tasked with regulating the waves resulting from such vessel operations.

The recent study by Macfarlane and Graham-Parker [1] compared the height and period of the maximum wave created while a monohull accelerates through the trans-critical depth Froude regime (in water of constant depth and infinite width) against those for the same vessel operating at a constant super-critical speed. It was concluded that notable transient effects occurred during acceleration, such as a 30-65% increase in height of the maximum wave compared to the same vessel operating at constant speed and finite water depth. The period of this wave also increased, but by the more modest rate of 20-30%.

The study by [1] found that this increase in both height and period occurred at both super-critical speeds investigated and for each of seven acceleration rates, which covered a realistic range of acceleration distances (between 2 and 14 boat lengths).

It is not unusual for vessels operating on waterways with sensitive shorelines to be required to meet specific regulatory criteria in terms of wash generation [4]. Such criteria are based upon the characteristics of the waves generated when the vessel travels at constant speed (and water depth). This approach is well justified as there is a need to make a fair and rational assessment, and this can only be achieved when the number of variables is limited to those most critical. Most of the criteria adopted over the past decade or two are based on both the height and period of the maximum wave (often in terms of energy, which is equally proportional to both these parameters)[5, 6]. Thus, the significant increases in both height and period found when a vessel accelerates will almost certainly result in the criteria being exceeded, albeit for a finite duration. Thus, there may be specific circumstances where the potentially more damaging waves generated as a vessel accelerates should be investigated further.

To date, the study has only involved a single hull form: a typical prismatic monohull. Given the significant findings, particularly the notable increase in both the height and period of the maximum wave when accelerating, there is a need to confirm if similar effects occur for other hull forms.

The primary aim of this present paper is to expand the study to determine if similar transient effects occur during acceleration for other hull forms. This is attempted by repeating a similar series of scale model experiments on a very different hull form to the original monohull: that of a typical ‘low wash’ catamaran ferry. Such craft are often used as passenger/ commuter ferries on rivers and other sheltered waterways where the wash they create has been of concern to property owners and other users of the waterway [1, 3].

Interestingly, the study by Macfarlane and Graham-Parker [1] found no such increase in wave characteristics when the same monohull decelerated from a super-critical speed back through the trans-critical speed zone. It has been assumed that this would also be the case when other hull forms decelerate, such as the selected catamaran model, so the present study focuses only on the acceleration case.

The systematic experimental campaign performed in [1] was also useful to inform the model test community about the transient effects when accelerating a ship model within a finite water test facility, such as a towing tank. For example, regardless of the acceleration rate, the wave pattern did not stabilise at a steady-state until the model had travelled a distance of approximately 3 or 4 boat lengths after the model had achieved the desired steady-state (target) speed. This practical outcome in regards to experiment design supports the findings of Calisal [7] who recommended that a ship model travel a distance before wave data collection is commenced to avoid the effects from the initial acceleration waves. The additional data acquired in the present study for the catamaran model permitted further investigation into this matter.

SHIP GENERATED WAVE PATTERNS

The general form of the waves generated by a ship or boat is dictated by the combination of vessel speed and the water depth beneath the vessel [8]. There are four main categories, starting with the sub-critical zone, where the water depth is considered deep and the well-known Kelvin wave pattern is produced. Here the depth Froude number is sub-critical (Fr_h < approximately 0.7). When approaching the critical speed ($Fr_h = 1.0$), a vessel operates in the trans-critical zone (approximately $0.7 < Fr_h < 1.0$) where the propagation angle of the divergent waves increases, leading to an increase in wave period. At the depth critical speed, large transverse waves with crests orthogonal to the direction of the vessel can be produced. This very specific case is rarely seen for extended periods in reality due to the fact that conditions such as water depth can vary and the dramatic increase in resistance: either the vessel struggles to maintain critical speed or it will overcome the resistance hump and enter the super-critical speed zone.

When a vessel operates at super-critical speeds, where Fr_h is greater than 1.0, the waves become long crested, in contrast to the short-crested waves of the sub-critical wave pattern, and transverse waves are no longer produced because of the depth-limited wave speed. Each of the wave pattern regimes are shown in simplistic form in Figure 1.

HULL FORMS

Body plans of the two hull forms utilized in this study are provided in Figure 2, with one of the symmetric demihulls of the catamaran on the left and the monohull from [1] on the right. It should be made clear that the purpose of the present study is not to compare the respective wash of a monohull and catamaran – if that were the aim then these hull forms would not represent a realistic or fair comparison of two vessels having similar capacity or purpose. The two hulls were selected as they are representative of roughly opposite ends of a wide range of 'typical' hulls: the monohull has a slenderness ratio that would be among the lowest practical (i.e the hull is relatively very short and heavy), while the catamaran has a high slenderness ratio, where the vessel is constructed as long and light as practical: typical of some present-day commuter catamaran ferries.

These key differences are reflected in the principal particulars listed in Table 1. Of note, the mass displacement of both scale models is roughly the same (at approximately 10.4 kg), but the waterline lengths differ greatly (1.822 m compared to 1.00 m), hence resulting in significantly different slenderness ratios (8.46 compared to 4.79 respectively). The relatively short and heavy monohull model was originally selected for the study presented in [1] as it should exaggerate any transient effects that may occur during the acceleration phase. Having now established that these effects are significant, the present study aims to assess whether they are as significant for this very different hull form, one which has been specifically designed for minimum wash.

METHODOLOGY

As with the earlier work reported in [1], wave characteristics for the catamaran are quantified by performing physical-scale model experiments in the 35 x 12 m (length x width) shallow water basin at the Australian Maritime College, University of Tasmania. The same constant water depth of h = 0.30m and two forward speeds of 2.0 and 3.0 m/s were adopted as this allows the investigation to cover typical sub-critical, trans-critical, and super-critical depth Froude numbers. Similarly, water surface elevations are acquired at many longitudinal locations at the same fixed transverse distance from the sailing line of the model. Given that the previous work concluded that there was essentially no increase in maximum wave height or period while the monohull model decelerated from a super-critical to sub-critical speed, it was assumed that a similar result would be found for the catamaran model adopted in the present study (NB: *it was confirmed through a limited number of experiments that this was the case; results are not presented here*). As such, of the four primary test scenarios performed in [1] for the monohull, only the following two were investigated for the catamaran hull form:

- accelerate from a stationary position to a low super-critical speed, where the critical speed was marginally exceeded (Fr_h = 1.17),
- accelerate from stationary position to a higher, well developed, super-critical speed (Fr_h = 1.75).

A longitudinal array of eight equi-spaced conventional two-wire resistance-type wave probes were positioned parallel to the sailing line of the model. The distance between the probes and the model sailing line remained constant for both the tests on the monohull and catamaran models. A plan view of the general layout of the facility and test apparatus is presented in Figure 3. The model was accelerated at a constant rate over the prescribed distance (e.g., four boat lengths) from a stationary starting position located at x = 0 m (2.0m before the first wave probe, LWP1). After the desired speed had been reached, it remained constant until the model was well beyond the last wave probe (LWP8) before the test was stopped. In each case a total of seven different acceleration rates (distances) were investigated, as detailed in Table 2.

The eight wave probes that form the longitudinal array were spaced 2.0m apart. As was the case for the monohull tests reported in [1], to acquire a time-series record of the water surface elevation at many more probe positions, additional tests were performed with the starting position for the ship model offset. A total of four different starting positions were adopted, allowing data to be obtained at 32 different longitudinal locations at 0.5 m increments between 1.5 and 17.0 m from the nominal model start position (refer Figure 3).

A typical time series record of the water surface elevation from a single wave probe is presented in Figure 4. Here the maximum wave is shown with definitions of the maximum wave height, H_m, and period, T_m.

RESULTS AND DISCUSSION

As was the case for the monohull model, a total of seven different acceleration distances were investigated for the high-slenderness ratio catamaran model at each of the two steady-state (target) speeds (refer Table 2). To assist in describing the analysis process, the resulting maximum wave heights at each of the 32 longitudinal locations (wave probes) from the model start position for just a single acceleration distance are plotted as a function of the distance from this start position in Figure 5. In this example, the dashed blue curve shows the model speed increasing from zero to the desired Fr_h value of 1.17 (right-hand axis) over the distance of 6 m, after which the speed remains constant (the acceleration was constant while the velocity increased linearly and the model position was quadratic in time).

The experimental points (red squares) indicate the maximum wave height at multiple locations along this acceleration distance and beyond. Unlike the speed, this wave height clearly does not increase linearly, but reaches a peak approximately 4 m (x = 9.5-10.5 m) after the point at which the steady state speed was achieved (x = 6 m). The dashed horizontal black line in Figure 5 represents the maximum wave height for the steady-state speed (acquired from other runs). This figure shows that a peak in maximum wave height occurs as a result of the acceleration phase that is significantly larger than the peak maximum wave height that occurs at the steady state speed. It can also be seen how the maximum wave height gradually decreases following this peak until it approximately equals that of the steady-state case (as expected). This increase in maximum wave height is believed to be due to transient dynamic effects that occur while the model accelerates (and slightly beyond as the model dynamics stabilise), such as additional hull resistance and increased running trim. It is also feasible that some of this increase in height is due to interference between the divergent and transverse wave systems.

The following figures present similar data for a range of different acceleration distances. The maximum wave height results are plotted against distance from the start position for all seven different acceleration distances at the speed of Fr_h of 1.17 in Figures 6 and 7 (results are split into two plots for clarity). Similarly, the results for the higher speed (Fr_h = 1.75) are presented in Figures 8 and 9. It is clear from the results in all four figures that the peak in maximum wave height created as a result of the acceleration phase is significantly higher than the steady state case for all seven acceleration distances.

These findings for the catamaran model are generally consistent with that of the monohull model presented in [1]. In order to further investigate whether the degree of increase in wave height is similar for these two very different hull forms, the percentage increase in maximum wave height (over the steady-state case) is plotted as a function of the acceleration distance for both steady-state Fr_h values of 1.17 and 1.75 in Figure 10. The most salient point from this figure is that there is a notable increase in maximum wave height for all cases during the acceleration phase, regardless of hull form, speed or acceleration distance. The magnitude of this increase varies considerably, from a minimum around 15%, up to a maximum in excess of 80%. For most cases the percentage increase in height was greater for the catamaran than the monohull at the corresponding depth Froude number, but it should be noted that the absolute wave heights were notably less for the long-slender catamaran model (as expected). Thus, the values for percentage increase for the catamaran may be more susceptible to small changes in height and variances in experimental uncertainty.

It is now widely accepted that both the height and period of the generated waves are of equal importance when it comes to assessing the potential impact of vessel generated waves [2, 4]. From the results presented above, it is clear that there will be an increase in wave height during the acceleration phase. Further analysis of the experimental data has quantified the corresponding period for the maximum waves for each acceleration distance and speed for both vessels. The results are summarised by presenting the resultant percentage increase in period of the maximum wave, as presented in Figure 11. Similar to the height of the maximum wave, the corresponding wave period also clearly shows an increase during the acceleration phase over that of the steady-state case. All acceleration distances for both steady-state speeds and vessels resulted in an increase in wave period between approximately 15 and 30%, with slightly larger increases occurring at the longer acceleration distances.

These increases in both wave height and period during the acceleration phase will lead to an increase in wave impact due to the subsequent increase in the wave-energy flux. As a result, it is almost certain that higher and potentially more damaging waves are created as a vessel accelerates to a super-critical speed (in finite water depths) than is the case when the same vessel operates at a constant super-critical speed. There also appears to be little practical means of avoiding this outcome; however, from the results presented in Figures 10 and 11 it appears the level of increase could be limited to a degree by minimising the distance over which a vessel is accelerated. For example in the case of the catamaran at the higher speed (Fr_h = 1.75), the results presented in Figure 10 show that the increase in height of the maximum wave for the shortest (most rapid) acceleration distance (approximately 40% increase) is roughly half that for the longest (slowest) acceleration distance (in excess of 80% increase over the steady state scenario). Minimising the acceleration distance is an approach previously recommended by PIANC [2]. There will of course be a limit to what constitutes a suitable acceleration rate in terms of passenger safety and the capacity of the propulsion system installed.

Implications for Experimental Procedures

The additional wave wake data now available for both the catamaran and monohull models has prompted further investigation into the determination of the time required for a scale model to stabilise to a steady-state following the acceleration phase. Analysis of this data has shed further light on the effect that the different distances for the acceleration phase has on the corresponding distance required after reaching a steady-state speed before the wave pattern is also considered to be steady.

The earlier study [1] concluded that a distance of 3-4 boat lengths is necessary, regardless of the acceleration rate. Further analysis suggests that this distance can vary considerably and that it is, not unexpectedly, dependent upon the distance the model is accelerated (and not necessarily on the length of the model). For example, both models took longer to stabilise following a rapid acceleration than they did an extended acceleration. To quantify a couple of the extreme cases, the distance from the model reaching a steady-state speed and the wave pattern achieving steady-state was in the order of 7 to 11 m for the most rapid acceleration rate (2.0 m), compared to an estimated 2 to 5 m at the slowest acceleration (14.0 m). Unfortunately, the limited length of the test facility hindered the investigation for the slower accelerations. The required constant speed also influenced the outcome; for instance, a steady-state was generally achieved in a shorter distance for the higher of the two speeds investigated (3.0 m/s).

CONCLUSIONS

Recent work by the authors concluded, through analysis of data acquired from a series of novel model scale experiments, that transient effects related to the characteristics of the waves generated by a vessel occurs when it accelerates. The result was a notable increase in both the height and period of the maximum wave compared to the waves generated by the same vessel operating at constant speed and water depth. These findings were based on the experiments performed using a scale model of a monohull possessing a low slenderness ratio (relatively short and heavy). The present study has confirmed that a similar result is found for a very different hull form, a high slenderness ratio catamaran (relatively long and light). This increase occurred for both hull forms at each of the two super-critical speeds and all seven acceleration rates investigated, covering a wide and realistic range of typical acceleration distances.

This outcome suggests that all marine craft, regardless of their shape or displacement, are likely to generate more energetic waves while accelerating compared to those generated while operating at a steady-state speed. This finding may have implications for those vessels that must meet regulatory criteria regarding wash impacts, particularly if the service requires the vessel to regularly accelerate from a sub-critical to super-critical depth Froude number, such as commuter ferries that service multiple passenger terminals on a sheltered waterway. In such cases, it may be necessary to consider the potential implications of these transient effects as part of the process to assess whether a vessel meets criteria imposed to regulate wash impacts.

These experiments may also aid the model test community in terms of providing advice on the required distance for a ship model to achieve a steady-state following the acceleration phase when performing tests in towing tanks or basins. In general, the model will take longer to stabilise following a rapid acceleration compared to the case when it is accelerated more gradually.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the Australian Research Council via Linkage Project LP150100502. We also thank the AMC technical support team for their valuable assistance preparing the experiments.

REFERENCES

[1] Macfarlane, G.J. and Graham-Parker, K.J., 2019, Marine vessel wave wake: transient effects when accelerating or decelerating, *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 145 (1).

[2] PIANC (Permanent International Association of Navigation Congresses). 2003. Guidelines for managing wake wash from high-speed vessels. Rep. Working Group 41, Maritime Navigation Commission. Brussels, Belgium: PIANC.

[3] Macfarlane, G.J., Cox, G. and Bradbury, J., 2008. Bank erosion from small craft wave wake in sheltered waterways. *International Journal of Small Craft Technology*. B. 150 (B2): 33–48.

[4] Macfarlane, G.J., Bose, N. and Duffy, J.T., 2014. Wave wake: Focus on vessel operations within sheltered waterways. *Journal of Ship Production and Design*. 30 (3): 109–125. https://doi.org/10.5957/JSPD.30.3.130055.

[5] Macfarlane, G.J. and Cox, G., 2007, An introduction to the development of rational criteria for assessing vessel wash within sheltered waterways, *Journal of Marine Design and Operations*, Part BII, IMarEST.

[6] Parnell, K. E., and Kofoed-Hansen, H., 2001, Wakes from large highspeed ferries in confined coastal waters: Management approaches with examples from New Zealand and Denmark. *Journal of Coastal Management*, 29 (3): 217–237. https://doi.org/10.1080/08920750152102044.

[7] Calisal, S. M., 1980, Some experimental results with ship model acceleration waves. Rep. USNA-EW-4-80. Annapolis, MD: Div. of Engineering and Weapons, US Naval Academy.

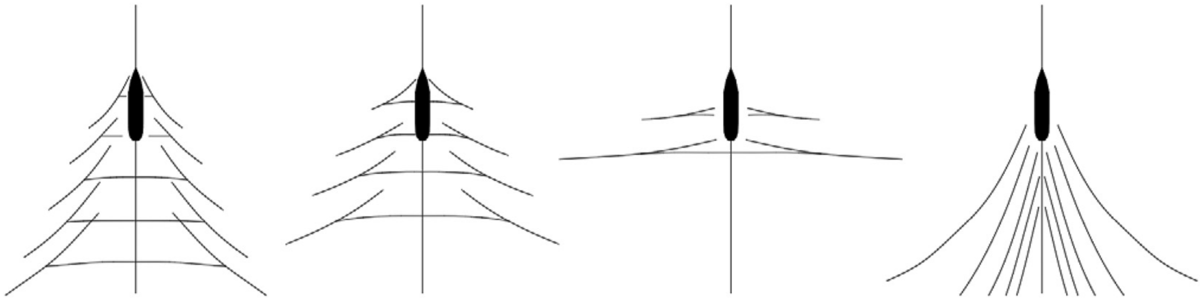
[8] Sorensen, R.M., 1973, Water waves produced by ships, Journal of the Waterways, Harbours and Coastal Engineering Division, Proceedings of the American Society of Civil Engineers, Volume 99, No. WW2, pp. 245 – 256.

TABLE 1: Principal particulars of scale model catamaran (AMC 98-16) and monohull (AMC 00-01)

Particular	*Catamaran (model AMC 98-16)*	*Monohull (model AMC 00-01)*
Length overall	1.852 m	1.102 m
Length waterline	1.822 m	1.000 m
Beam overall	0.456 m	0.337 m
Beam demihull	0.086 m	n/a
Draught	0.069 m	0.089 m
Displacement	10.25 kg	10.55 kg
Slenderness ratio	8.46	4.79

TABLE 2: Summary of test conditions investigated

Steady Speed (target)	**$Fr_h = 1.17$**	**$u = 2.0$ m/s**	**Steady Speed (target)**	**$Fr_h = 1.75$**	**$u = 3.0$ m/s**
Acceleration Rate (m/s^2)	Time to Accelerate (s)	Distance to Accel. (m)	Acceleration Rate (m/s^2)	Time to Accelerate (s)	Distance to Accel. (m)
1.00	2.00	2.0	2.25	1.33	2.0
0.50	4.00	4.0	1.13	2.65	4.0
0.33	6.00	6.0	0.75	4.00	6.0
0.25	8.00	8.0	0.56	5.36	8.0
0.20	10.00	10.0	0.45	6.67	10.0
0.17	12.00	12.0	0.38	7.89	12.0
0.14	14.00	14.0	0.32	9.38	14.0



$Fr_h > 0.7$ $0.7 > Fr_h > 1.0$ $Fr_h = 1.0$ $Fr_h > 1.0$

FIGURE 1: Vessel wave wake idealized with varying depth Froude numbers

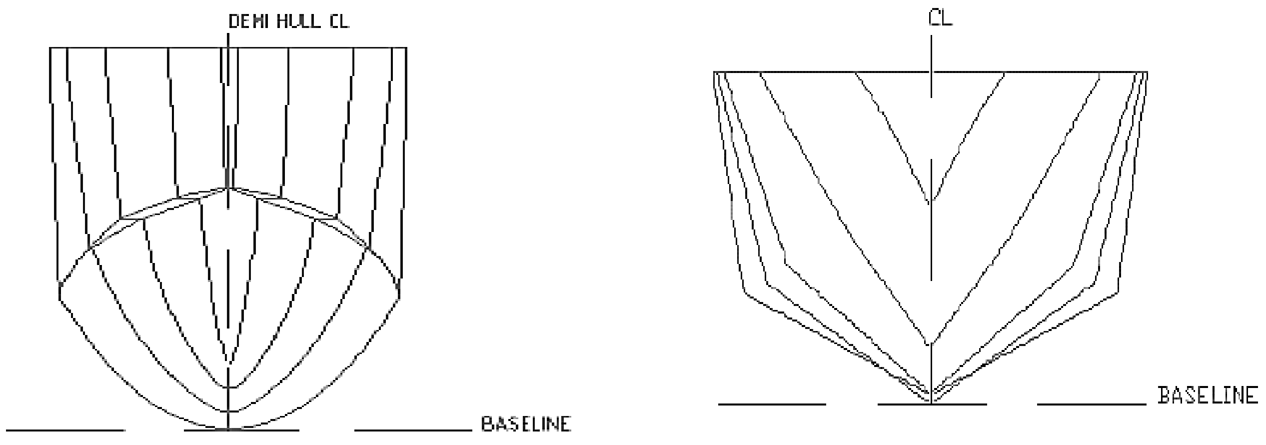


FIGURE 2: (left) Model AMC 98-16 demi-hull body plan, catamaran; (right) Model AMC 00-01 hull body plan, monohull (not to scale)

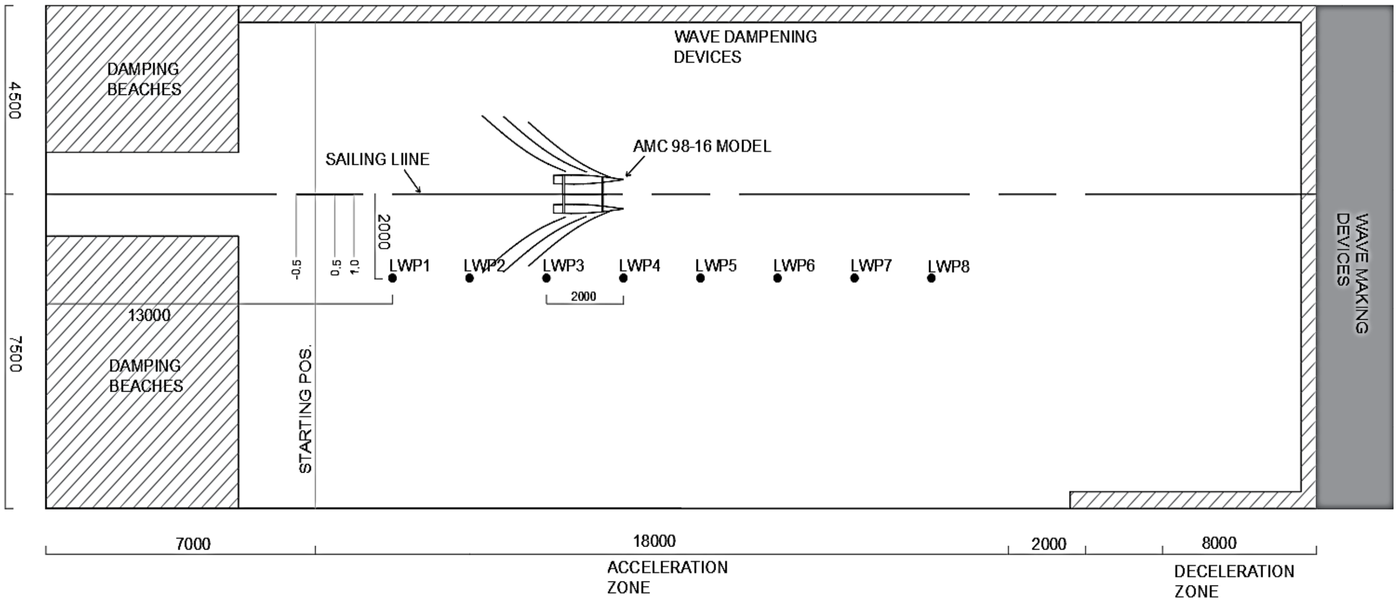


FIGURE 3: Plan view of the experimental layout and test apparatus setup at the Australian Maritime College's model test basin

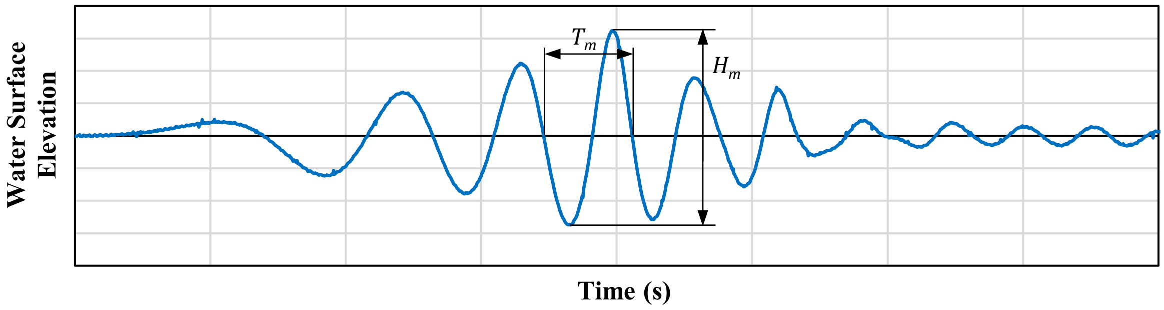


FIGURE 4: Typical water-surface-elevation time series recorded from a wave probe

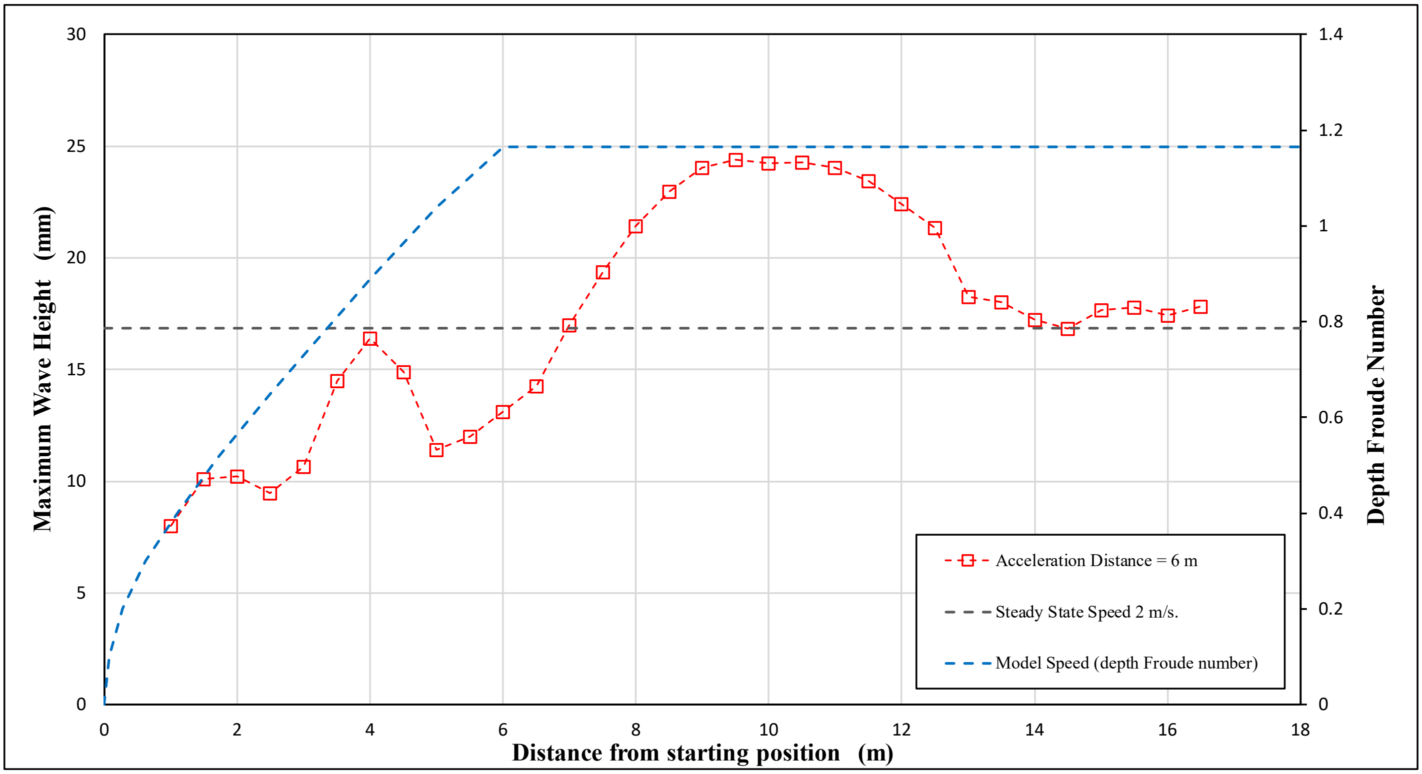


FIGURE 5: Sample of maximum wave height as a function of distance from the starting position for an acceleration distance of 6 m and steady speed with Fr_h of 1.17.

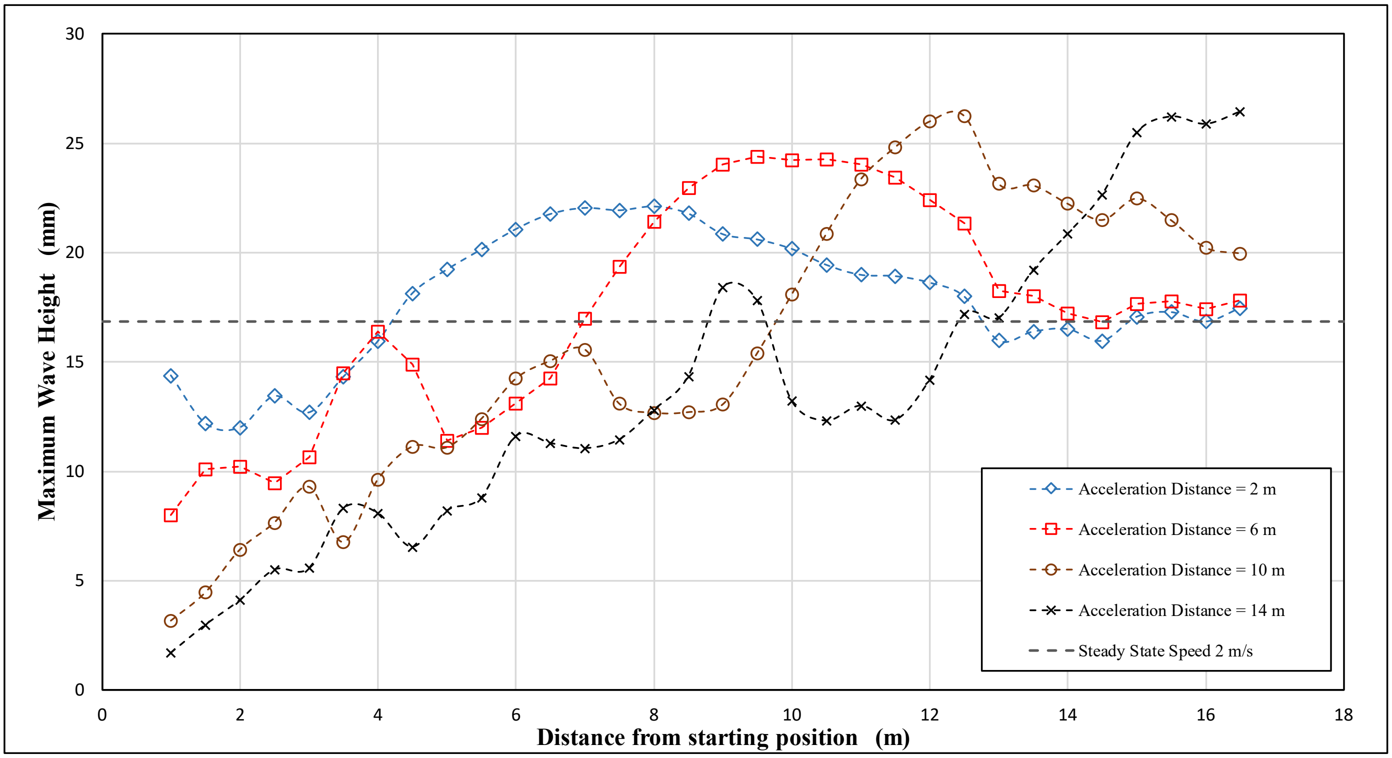


FIGURE 6: Plot of maximum wave height as a function of distance from starting position for acceleration distances of 2, 6, 10, and 14 m at steady state speed of Fr_h = 1.17.

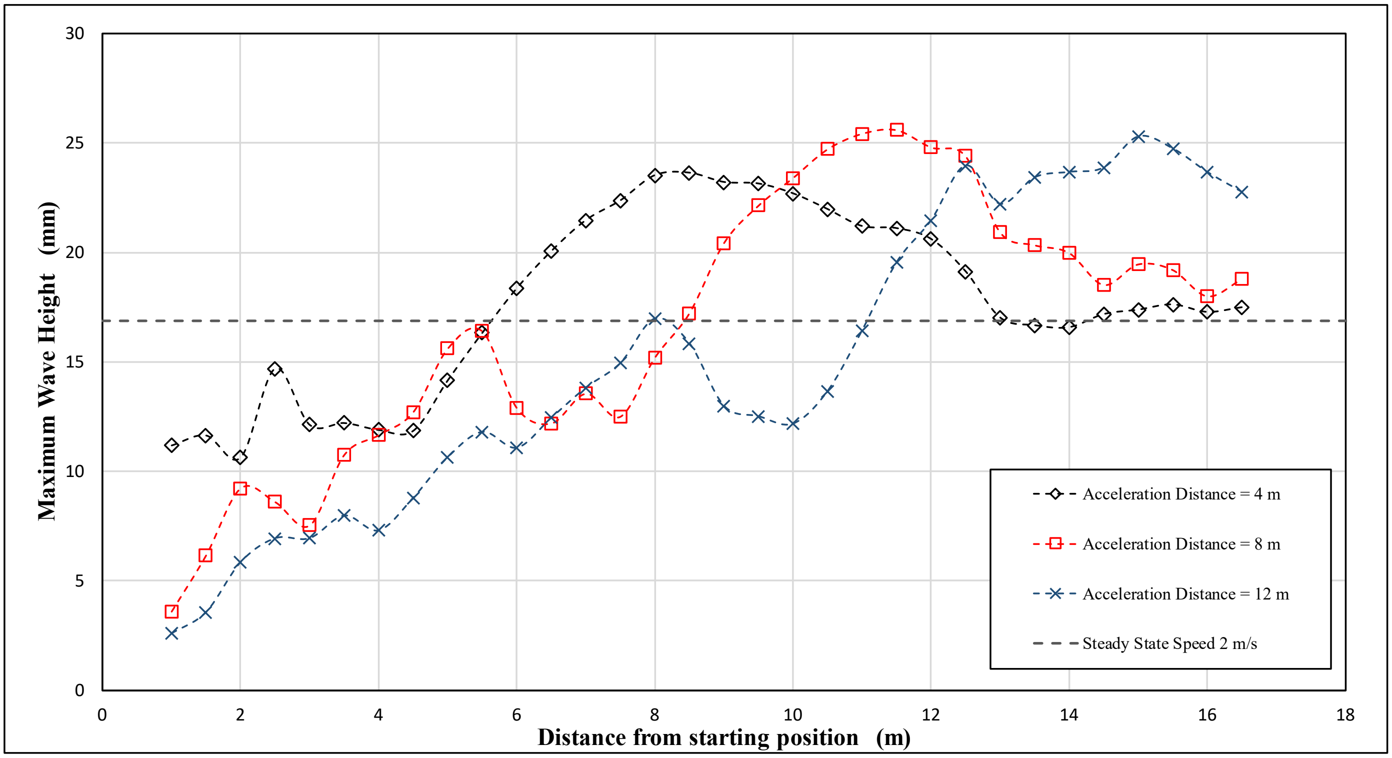


FIGURE 7: Plot of maximum wave height as a function of distance from starting position for acceleration distances of 4, 8 and 12 m at steady state speed of $Fr_h = 1.17$.

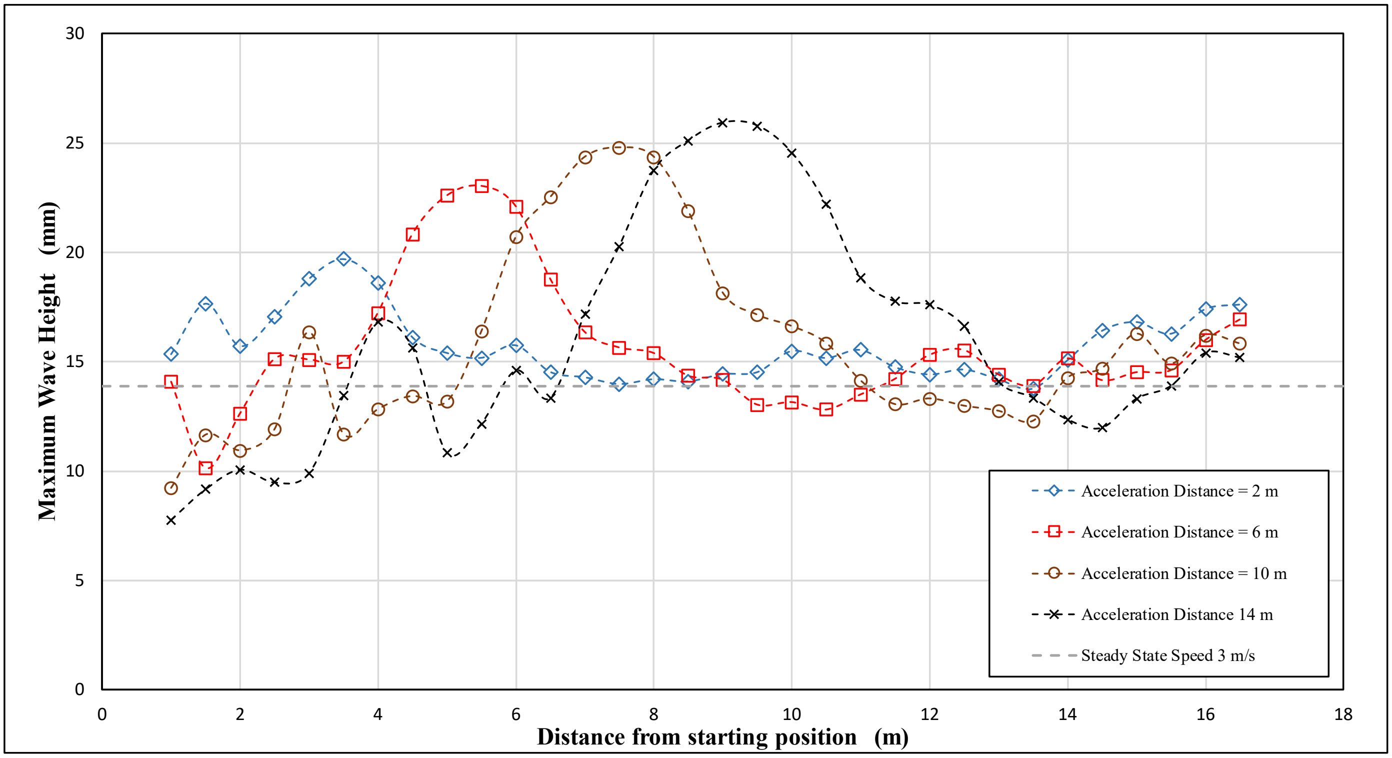


FIGURE 8: Plot of maximum wave height as a function of distance from starting position for acceleration distances of 2, 6, 10, and 14 m at steady state speed of $Fr_h = 1.75$.

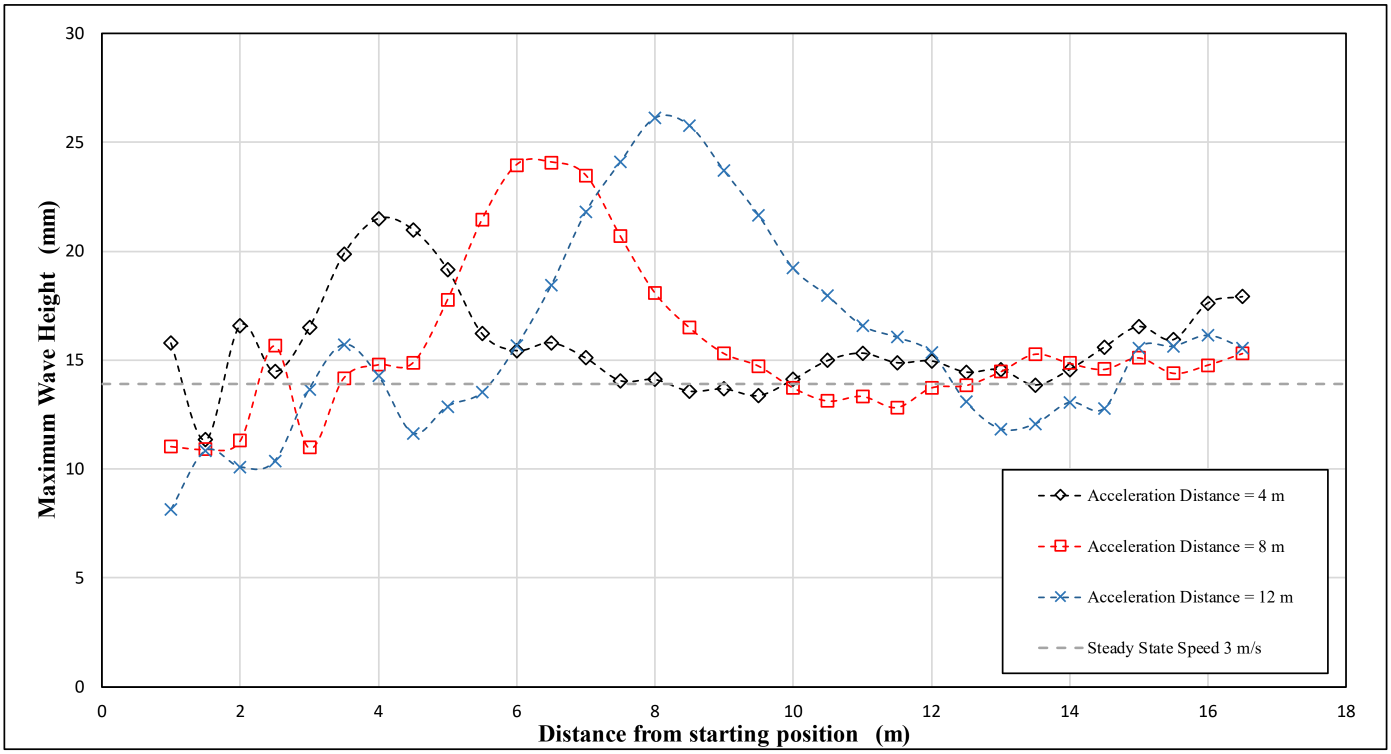


FIGURE 9: Plot of maximum wave height as a function of distance from starting position for acceleration distances of 4, 8 and 12 m at steady state speed of $Fr_h = 1.75$.

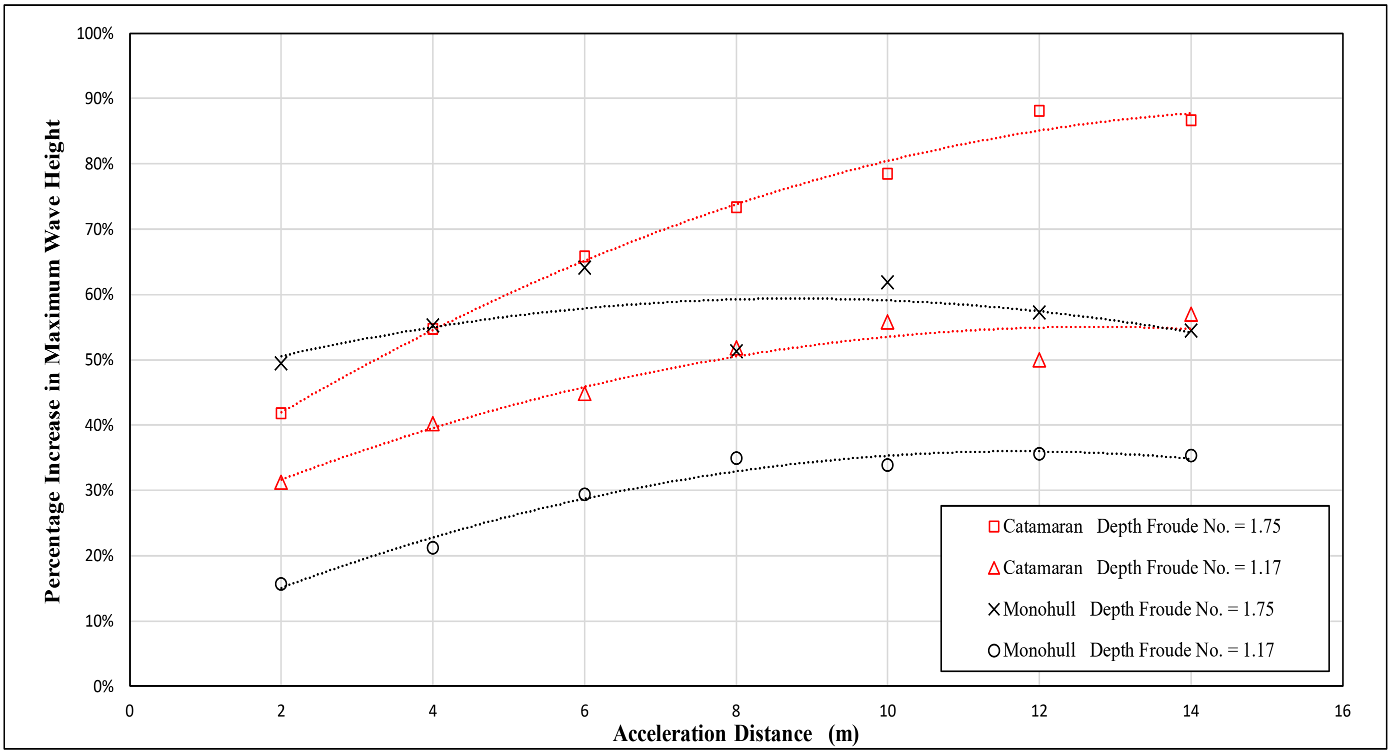


FIGURE 10: Plot showing percentage increase in maximum wave height during acceleration compared to steady state as a function of acceleration distance.

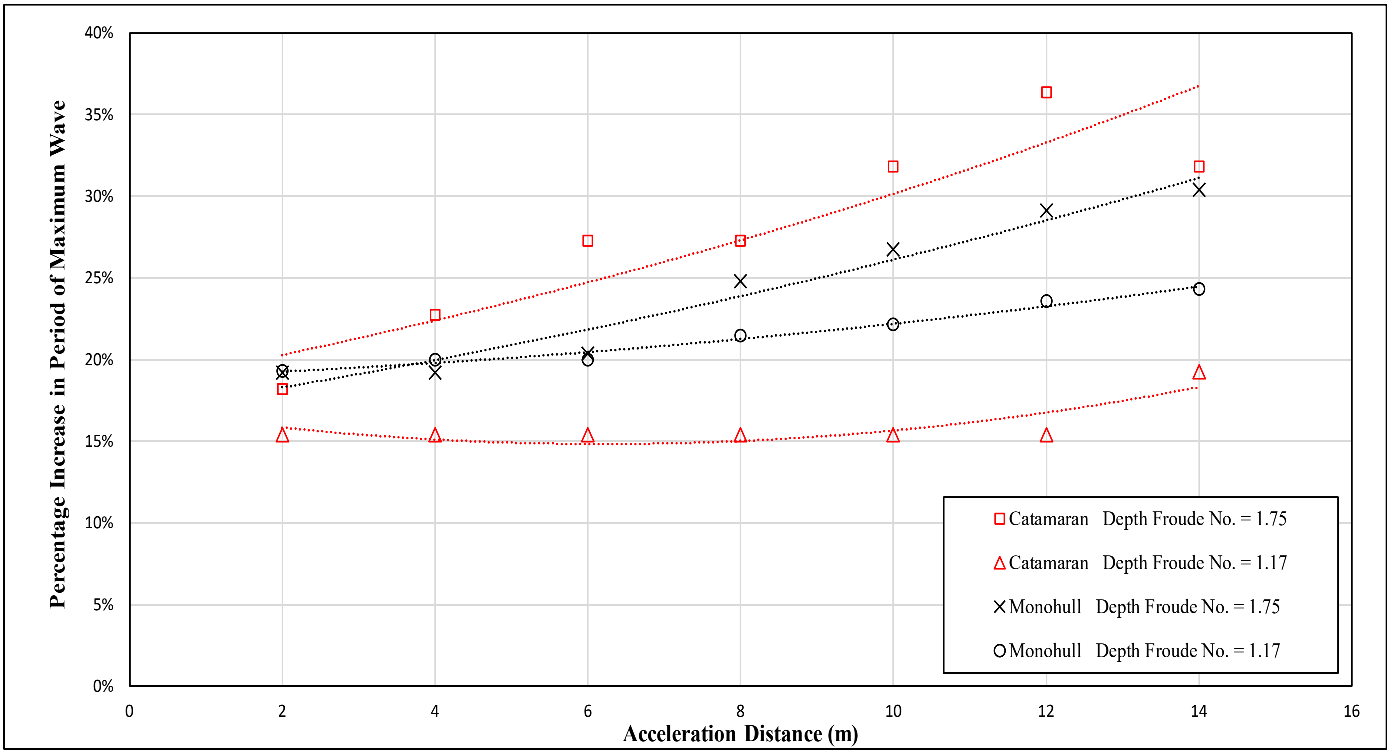


FIGURE 11: Plot showing percentage increase in period of the maximum wave during acceleration compared to steady state as a function of acceleration distance.