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Use of Simulations to Predict Lifeboat Survivability in Extreme Waves and the Effectiveness of Coxswain Performed Actions

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ABSTRACT: Simulations were used to investigate the performance of lifeboats in high sea states using a virtual wave tank. Numerical simulations were performed in regular and irregular waves to study launch performance in extreme weather conditions. Limitations in launch equipment and the role of the timing of coxswains' actions were investigated. The study indicated that the lifeboat may not be able to successfully launch when significant wave heights are above 8 m and the lifeboat is launched near the trough of a wave. High initial setback and continuous wave forces result in the vessel being unable to clear away from the launch platform. As wave heights increase, the amount of setback and time to exit the launch area increases. Over 35% of launches resulted in the lifeboat being unable to clear from the launch area when significant wave heights were 10 m or above. The study also identified that delay in completion of actions performed by the coxswain, such as releasing the lifeboat hooks and applying throttle, can increase setback and time to exit the launch area.

1 INTRODUCTION

The successful launch and clear away of a lifeboat in high sea states is affected by both the capabilities of the lifeboat and the actions taken by the coxswains. The effects of coxswain actions on the ability to complete a successful launch and sail away have not been fully investigated, nor have the limitations of the launching equipment in high sea states been fully explored. This paper investigates both.

Previous scale model experiments were performed to evaluate the factors affecting a successful lifeboat launch and sail away (Simões Ré et al., 2002, Simões Ré & Veitch, 2004, Simões Ré et al., 2008). These experiments investigated the limitations in launching considering factors related to wave height, launch configuration, and lowering speeds from the davit. The experimental studies used regular waves which is a simplification of real conditions where wave shapes are irregular. These studies also did not include the full range of sea states that are possible in offshore operations as wave heights were limited to 10 m. Additional studies used numerical simulations to study similar factors and explored the effect of timing of hook release and application of propulsion (Gabrielson et al., 2011).

Industry studies have identified that coxswain skill has an impact on a successful lifeboat launch, although benchmarking of skills is difficult due to limitations in training (Robson, 2007). Evaluating the impact of human performance and skills on a successful launch in high sea states is not practical. Due to the perilous nature of launching lifeboats in rough conditions, the role of the operator (coxswain) is not something that can be ethically investigated in field trials or experiments, nor practiced in realistic (rough) wave conditions. Due to the nature of model experiments, specifically the scaling of time, it is difficult to use model tests as a means to investigate time dependent human factors.

In this research simulations were used to explore the lifeboat performance in wave heights not previously tested in scale model experiments and field trials. The simulator is also used to study how the timing of actions performed by the coxswain, including applying the throttle and releasing the hooks, affect launch performance.

Details are first presented on the launch procedure and the performance measures discussed in the paper.

2 BACKGROUND

2.1 *Launch procedure*

As summarized in previous research (Simões Ré et al., 2002, Gabrielson et al., 2011), there are multiple phases of a lifeboat launch. They are as follows:

- Lowering phase: lowering the lifeboat from the davit system to the water surface.
- Water entry: starts when the vessel enters the water and the lifeboat becomes buoyant. During this phase, water fills the vessel hydrostatic release unit, and hydrostatic pressure moves a cable link to allow the hook release handle to open.
- Release: starts when the hook is released and the vessel is free from the fall wires.
- Sail away: vessel propulsion (throttle) is applied and the operator manoeuvres the vessel to a safe area away from the launch platform.

The launch starts when a brake wire is pulled and the vessel begins lowering from the davit. The vessel continues to lower until the vessel is in the water and a time count begins on filling the hydrostatic release. The hydrostatic release activates when the vessel remains buoyant for 3 seconds or longer. If the wave falls away from the vessel before it is buoyant, the hydrostatic release drains and the time restarts. Once the vessel is buoyant for three seconds, the hydrostatic release system allows the hook system to operate. A hydrostatic indicator on the hook release system moves providing a visual cue to the coxswain. The standard procedure is to release the hooks and then apply full throttle as quickly as possible and drive away from the launch platform.

This paper focuses primarily on the water entry, release, and sail away and considers the relationship between the actions performed by the coxswain and the timing of transition between the phases.

2.2 *Setback*

The experimental studies (Simões Ré et al., 2002, Simões Ré & Veitch, 2004, Simões Ré et al., 2008), identified that the amount of setback, or backwards trajectory of the vessel, increases in higher sea states when the launch position on the wave is near the trough on the lower part of the wave upslope. Wave and wind forces impact the vessel on water entry and can push the vessel backwards towards the launch platform if the waves are against the evacuation direction (a head sea). In head seas with wave heights of 6 m and above, setback can result in the vessel being pushed back to within critical safety zones of launch platforms. The amount of setback and likelihood of occurrence of setback increases with wave height.

Total setback can be a result of a single wave or multiple wave encounters may cause progressive setback before the vessel begins to move forward (Simões Ré et al., 2002). Figure 1 shows a sample trajectory plot of a launch to illustrate the case where a vessel experiences initial setback (SB), progressive setback, and is then able to progress forward. The vertical position is plotted on the Y axis, with vessel lowering to the still water line at y = 0. The horizontal displacement positive is the distance in the direction away from the launch platform. X = 0 is the starting horizontal position of the vessel when lowered. In this sample the vessel is setback (-ve x direction) on the first wave encounter, and the second wave encounter results in higher, or progressive wave setback. The vessel is then able to progress forward. The subsequent waves create some backwards displacement with each wave encounter, but the overall movement is in the +ve x direction away from the launch platform. Initial setback, progressive setback, and forward progress are used to describe results in this paper.

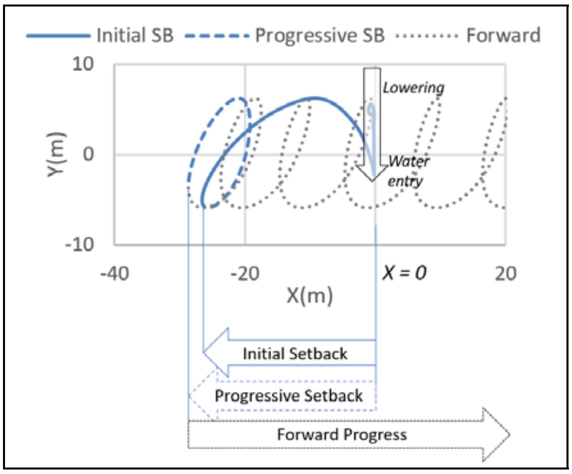

Figure 1. Progressive Setback

2.3 *Impact of launch position on wave*

Studies identified the impact of timing of release of the lifeboat at different points on the wave in a head sea (Simões Ré et al., 2002, Simões Ré & Veitch, 2004, Simões Ré et al., 2008). Launching on the trough of the wave can result in significant setback and launching on the crest of a wave results in minimal, or no, setback. The experiments also showed the effect of "wave shadowing," whereby the lowering speed of the vessel and the wave speed resulted in launches on the leeward side of the wave. With reference to Figure 2, most launches occurred between -60 and 60 degrees, on the wave upslope. In effect, it is difficult to launch on downslopes, which are favourable to good launches, and launches are more likely to occur on upslopes which result in large setbacks. As wave height or wave steepness increases, the zone of possible launch positions tightens.

Taken together, these findings indicated that the timing of the launch relative to the wave is very important. It should not be left to chance as it is something that is within the operator's ability to control, at least to some extent.

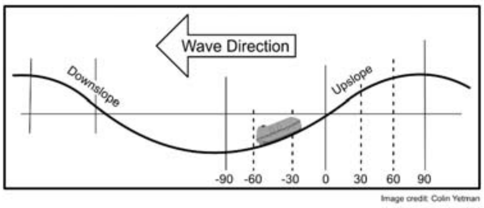

Figure 2. Launch Positions for Lifeboat Water Entry

2.4 *Performance measures*

The primary measure of performance in the study is setback. Additional measures are defined for this study based on target operational outcomes. These new measures are as follows, with reference made to Figure 3.

The first additional measure identifies launches which may result in contact with the launch platform and consequently may result in damage to the vessel or harm to the crew. Examination of launch platforms and launch configurations indicates that davit systems are placed to provide 20 to 40 m of clearance from the base of the platform. Setback greater than 20 m may result in impact with the launch platform or result in vessel being within a zone of high risk of impact. In Figure 3, X = 0 is the position directly below the launch area and X = -20 m is the distance travelled towards the platform, opposite the target evacuation direction. To evaluate performance for a given set of launches, the percentage of outcomes with greater than 20 m in setback (%Setbacks>20m) was calculated.

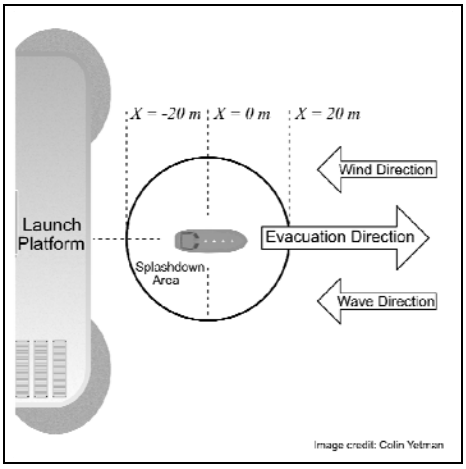

Figure 3. Performance Measures: Setback>20m and Clearance Time>60s

Another measure was introduced to evaluate whether the lifeboat is able to evacuate from the launch platform quickly. Clearing time is defined as the time required for the vessel to leave the splashdown area in the evacuation direction and reach a target distance, which is defined as 20 m from the launch position (X = 20 m in Figure 8). Timely clearance of the lifeboat from the launch area is desired to escape harm from hazards near the launch platform and to permit the launch of other vessels from adjacent davits. The percentage of occurrences with greater than 60 s of time needed to reach 20 m is calculated for a set of launches (%Clearance Times>60s). The amount of setback and clearing time to exit the splashdown area are related, as the vessel must travel a longer distance to exit the splashdown area if it is setback farther.

If no measure was recorded for this performance criteria, the vessel was unable to reach the escape line at X = 20 m. This outcome is defined as a failed clearance. A measure of failed clearance identifies a performance limit as the vessel is not able to progress forward in the wave environment tested. This limit is further discussed in the results.

3 SCOPE

With the advent of simulator technology, it is now possible to explore lifeboat and operator performance in weather conditions typical of their location of operation. Lifeboat simulators are designed with accurate numerical behaviour of vessel motions and wave environments. Trainees interact with realistic lifeboat equipment and perform actions as they would in a real vessel. Studies performed with a lifeboat simulator have evaluated how skills transfer from simulator training to real vessels (Magee et al., 2016) and how skills are acquired in initial training (Billard et al. 2019). Recent studies have focused on how training affects coxswain skill acquisition and launch performance in moderate weather environments (Billard et al., 2018, Billard et al., 2020). These studies have not investigated the impact of human factors in high sea states.

Simulators are increasingly used to train lifeboat coxswains. Trainees can practice and improve timing of actions, such as releasing the hooks and applying the vessel throttle. There is increased knowledge of the times taken to complete tasks in a lifeboat launch via data collected through simulator training programs. The timely or delayed performance of these actions is expected to impact the amount of lifeboat setback and the time to clear from the launch area. Evaluating how the timing of these actions affects the launch outcomes will help to define training objectives.

As in other studies, simulators can explore scenarios where data is scarce or difficult to obtain (Groth et al. 2014) and can specifically extend knowledge of coxswain and lifeboat performance to high sea states. The study of human factors using simulation to evaluate performance is evident in other operations including flight (McClernon et al. 2011), medical (Stefandis et al. 2007) and marine (Sellberg, 2017) training. This research shows an example of how simulations can be used to evaluate how operator actions impact the ability to successfully launch a lifeboat.

The purpose of the research was to use numerical simulations to 1) assess the performance and limitations of lifeboat launch systems in extreme seas and to 2) study the impact of the timing of human actions on the launch and sail-away of the lifeboat.

A numerical simulator, a Virtual Wave Tank (VWT), was designed to emulate the lifeboat and wave conditions performed in previous research (Simões Ré et al., 2002, Simões Ré & Veitch, 2004, Simões Ré et al., 2008). Validation was performed to ensure the measured setback is comparable between the numerical simulator and experimental studies performed in a wave tank. Comparisons were made for multiple wave heights and launch positions on the waves. The kinematics of the vessel in the VWT were also compared with results from the experimental studies.

After validation, we performed three investigations with the Virtual Wave tank to study the effect of wave height and timing of coxswain-performed tasks on launch performance. The first investigation built on the outcomes of the experimental tests (Simões Ré et al., 2002) and extended the regular wave conditions to waves up to 16 m. Simulations were then performed in irregular sea states with significant wave heights of 6 to 12 m to investigate launch performance in irregular waves with 100-year return period extreme wind speeds based on historical data of weather conditions in the North Atlantic (C-Core, 2015). The third investigation studied how the timing of human actions affected the likelihood of a successful launch. The time taken to apply propulsion (throttle) is varied. The time to release the lifeboat hooks once the vessel is buoyant in the water and able to be released is also varied. The impact of delayed response in applying the throttle and hook release is studied. Comparison are also made between cases where throttle is applied prior to release of the hook to investigate how applying an initial propulsion force influenced the ability to complete a successful evacuation.

Performance is evaluated using the measures identified in the previous section. The investigations focused on performance in head seas.

The following research questions are investigated:

- What is the expected setback of a lifeboat in extreme regular waves and irregular waves?
- How is the time to clear the lifeboat from the launch structure affected by sea state?
- How does delay in lifeboat throttle and hook release affect launch and evacuation of a lifeboat?

3.1 *Virtual Wave Tank (VWT)*

The VWT simulation environment used in the study is a 3D physics-based engine that was specifically created to model the motion of small crafts in marine environments. Physics models were derived from studies of vessel motions in waves, including scale model and full-scale testing of the vessels (Simões Ré et al., 2002, Simões Ré & Veitch, 2004, Simões Ré et al., 2008, Magee et, al. 2016). Numerical models for all phases discussed in the launch procedure were included in the simulation environment.

Numerical models were implemented to provide physic-based responses and timings during the launch phases. The vessel behaviours at water entry were modelled to include the tension in the lowering wires before the hook is released, the dynamic behaviour of the lifeboat as it interacted with the water surface, and the release of the vessel. The propulsion and hydrodynamic behaviours of the vessel once in the water were also modelled. Previous studies have validated the manoeuvring and performance characteristics of the vessel modelled in this study are representative of the behavior of the real lifeboat (Billard et al. 2020). Models are resolved on the computer GPU to allow for high-speed and high-resolution wave meshes to calculate hydrostatic and hydrodynamic forces.

The vessel was modelled with dimensions, weight, propulsion and steering to study the lifeboat's ability to manoeuvre in the environmental conditions considered. The vessel modelled in the simulator was a fully loaded lifeboat with length, weight, and displacement parameters closely matched to the vessel used in experiments performed by Simões Ré et al. (2002).

A twin fall davit was modelled with fall wires attached to the fore and aft hooks of the vessel during lowering. The lowering speed of the vessel was kept constant at 1.0 m/s. The launch height of the davit was 35 m. The lowering of the lifeboat is normally controlled by pulling a brake release from within the lifeboat to extend the fall wires. In the simulations, the fall wires continued to extend until the hook is released. This is a normal procedure to make sure the vessel begins to float, and to reduce the likelihood the vessel is only temporarily buoyant if the wave falls away from the lifeboat.

A virtual agent was used to perform the actions of the coxswain in the simulator. The virtual coxswain could be programmed to release the hook, manipulate the throttle and attempt to steer the vessel to desired headings. Timings could be set to perform actions instantaneously or with delays, or in different orders (i.e. applying throttle before hook release). The resultant behaviour of the vessel was determined by the physics engine which applies and resolves forces depending on the actions taken by the coxswain. As an example, a delay in moving the throttle ahead after the hook was released resulted in a delay in the propulsion and the vessel was free to drift until propulsion was applied. When manoeuvring, the virtual coxswain attempted to maintain a constant heading and used corrective steering to come back to a heading if the vessel veered off course. The study assumed steering was maintained to target a heading directly into the waves and away from the launch platform.

4 STUDY METHODOLOGY

The study included two stages: 1) validation of the simulator measures with data from experimental studies, and 2) using the simulator environment to perform new studies. Three studies, or investigations, were performed with the VWT to study the lifeboat performance in higher sea states and to consider the timing of coxswain actions. The investigations varied wave shape, wind speed, and coxswain timings to study the effect of these variables. Comparisons are made between each study to illustrate results.

4.1 *Validation – Simulator and scale model experiment*

Comparisons are made between the outcomes of scale model testing performed in previous research to validate the simulation. Data sets were created using the VWT using a stokes regular wave, with wave heights from 2 to 10 m, and wind speeds matching the scale model experimental tests (Simões Ré et al. 2002). Validation is performed using the following comparisons between the simulator outcomes and the scale model tests:

1. maximum setback for each wave height;
2. setback for multiple launch positions on the wave; and,
3. checking the trajectory of the vessel during water entry and sail away.

4.2 *Investigation 1 – Study of individual wave setback in high sea states, regular waves*

The first set of test cases investigated the impact of environmental conditions on lifeboat setback with testing extended to higher sea states and wind speeds representing storm and hurricane conditions. Test cases were performed with a stokes regular wave shape with wave heights ranging from 2 m to 16 m. The approximate wave steepness in each case was 1/20. The simulation used wind speeds and wave heights similar to the parameters used in the experimental studies (Simões Ré et al. 2002) for wave heights up to 10 m. The wave heights and wind speeds were extended to wave heights of 12, 14, and 16 m, using average wind speeds for observed wave conditions (C-Core, 2015). The parameters for each wave tested is provided in Table 1.

Table 1. Series 1 - Regular Wave Parameters

Wave Height (H_w) [m]	Wave Period (T) [s]	Mean Wind speed [m/s]
2	5	10
4	7	12
5	8	16
6	9	17
7	9	18
8	10	19
10	11	22
12	12	28
14	13	30
16	14	33

48 launches were performed for each wave height. For each launch, the starting time of the launch was varied resulting in a different launch position on the wave, with launches covering a full wave cycle of one wave period. The maximum time permitted was 240 s (4 minutes).

4.3 *Investigation 2 – Study of lifeboat performance in irregular 100yr seas*

The second set of simulations investigated the launch and sail away phase of the lifeboat in irregular shaped head seas and high wave heights. The lifeboat was lowered and launched into a sea state with a defined significant wave height (Hs) and irregular wave pattern. The irregular wave shape included dominant waves and lower frequency minor waves. Waves were generated from a fast Fourier transform to generate the desired Hs, as measured by the mean wave height of the highest 1/3 of the waves. Individual wave heights could exceed Hs. The maximum wave heights in the test cases are presented in table 2. The peak period (Tp) is the dominant wave with the highest energy. Wave heights of 6 m to 12 m were selected to study vessel performance where high setback is likely. Wind speeds were taken to be representative of 100-yr occurrences in the North Atlantic (C-Core, 2015) and are higher than the winds used in the regular waves.

For each wave height, simulations were performed with three different wave patterns. Each wave shape had the characteristic parameters identified in Table 2. 48 launches were performed for each wave pattern to cover a full cycle of a dominant wave. The data for each wave pattern was combined for analysis, resulting in 144 launches for each combination of wave height and wind studied.

Table 2. Series 2 - Irregular Wave Parameters

Significant Wave Height (H_s) [m]	Max Wave Height [m]	Peak Wave Period (Tp) [s]	Mean Wind Speed [m/s]
6	8.7	9	20
8	11.5	10	25
10	13.2	11	30
12	15.8	12	33

4.4 *Investigation 3 – Study of human performance on evacuation performance in irregular 100yr seas*

The third set of simulations varied the time to complete actions performed by the coxswain in the lifeboat launch and clear away. The virtual coxswain in the VWT simulation was programmed to perform the hook release and to move the throttle from neutral to full propulsion at controlled times. Data collected from training courses performed by Virtual Marine has indicated that the timing of release of hooks can vary from 1 to 5 seconds following an indication that the hydrostatic bladder has filled, and the hook release system can be operated. This delay can be caused by a combination of human reaction time, difficulty in operating the hook release handle, or time taken to perform other tasks. Training records have also identified the time to apply full throttle can vary between coxswains. Delay in application of throttle following hook release means the propulsion of the vessel is delayed, and the vessel is free to drift if the hooks have been released.

The study first investigated the application of throttle and delay in hook release separately. Throttle delay cases assumed the hook was immediately released when the hydrostatic bladder had filled, and times presented are relative to the time of hook release. The time to throttle (TT) is the amount of time the vessel is untethered by the fall walls and free to drift before throttle is applied. For the hook release cases, time to hook release (TR) was relative to the instant the hydrostatic bladder has filled (t = 0), and the vessel remained tethered until release of the hook.

In these cases, throttle was applied immediately on hook release. The timings are summarized in Table 3.

Table 3. Delayed Throttle and Hook Release Cases

Label	Hydrostatic Ready	Time to Throttle (TT)	Time to Hook Release (TR)
TT2	t = 0 s	t = 2 s	t = 0 s
TT4	t = 0 s	t = 4 s	t = 0 s
TR2	t = 0 s	t = 2 s	t = 2 s
TR4	t = 0 s	t = 4 s	t = 4 s

These initial cases studied the delayed performance of actions normally taken in a launch sequence where the typical launch procedure is 1) wait until the vessel is buoyant, 2) release the hook and 3) apply throttle.

An additional series of tests was performed to investigate the impact of early application of throttle, prior to release of the hooks. This emulates an operator decision to apply propulsion before the lifeboat is released from the fall wires. This procedure has been suggested by experienced operators as a means to give the vessel initial thrust to combat wave forces, albeit not a standard operating procedure.

In these cases, the virtual coxswain applied the throttle fully when the vessel was buoyant (i.e. hydrostatic interlock had filled, t = 0), and remained tethered. Four use cases with different combinations of time to throttle (TT) and time to hook release (TR) are identified in Table 4. Early throttle provided a propulsion force before the vessel becomes untethered, and the hook was released at a time following the throttle.

Simulations were performed for the irregular waves identified in Table 2, with Hs from 6 to12 m. Data sets were again acquired for three wave patterns and combined for analysis, resulting in 144 launches for each case and wave studied.

Table 4. Early Throttle Cases

Label	Hydrostatic Ready	Time to Throttle (TT)	Time to Release (TR)
TT1-TR2	t = 0 s	t = 1 s	t = 2 s
TT1-TR3	t = 0 s	t = 1 s	t = 3 s
TT2-TR3	t = 0 s	t = 1 s	t = 3 s
TT2-TR4	t = 0 s	t = 2 s	t = 4 s

5 RESULTS

In this section summarize the outcomes of the investigations are summarized and discussed. Comparisons are made between outcomes of the studies to illustrate the effect of the variables studied. Multiple measures are discussed to provide insights on how the outcomes are related and to make comparisons between the individual investigations.

5.1 *Results – validation, simulator and scale model experiment*

Comparisons were made between the simulator measures and the experimental studies performed by Simões Ré et al. (2002) to validate the measures and behaviours observed in the simulator are similar to the experimental studies. A sample of the validation cases are discussed.

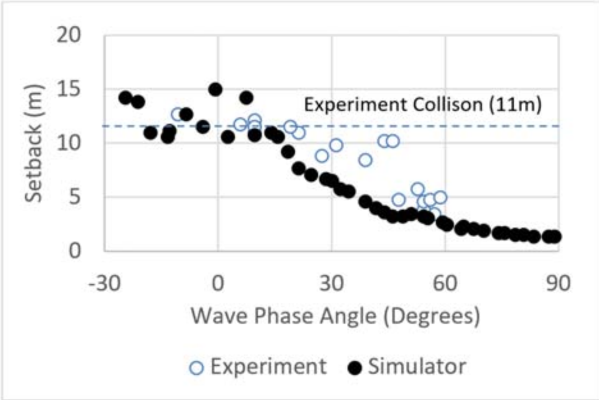

Figure 5. Setback vs. Wave Phase Angle, H_w = 6 m

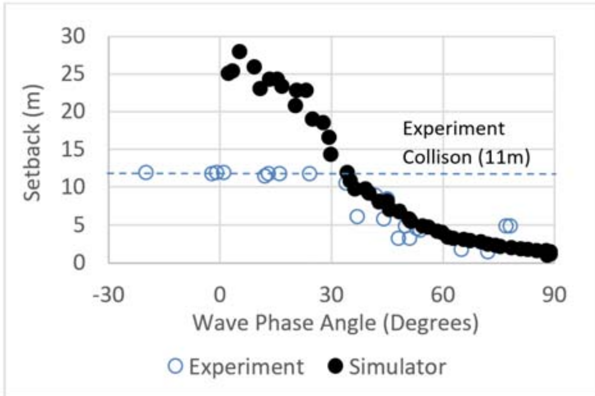

Figure 6. Setback vs. Wave Phase Angle, H_w = 10 m

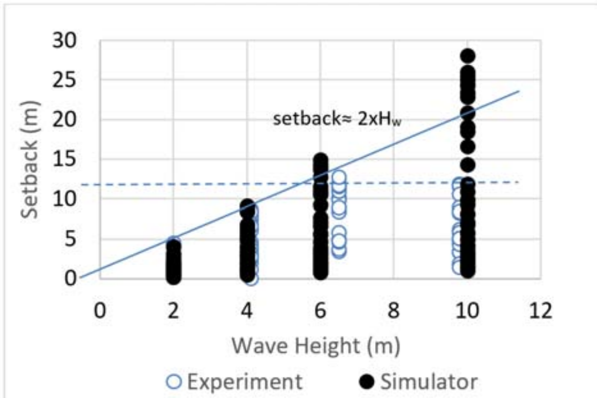

Figure 7. Setback vs. Wave Height

Figures 4 and 5 show the measured setback for various launch positions on a regular wave, with 90 degrees being the wave crest and -90 degrees being the wave trough. The comparisons show the observed behaviour is the same in the simulator (Simulator) compared to the scale model experiment (Experiment), with setback increasing as the vessel is launched closer to the trough of the wave. Of note, the setback in the experiment was limited at approximately 11 m due to the experimental setup, with the model impacting the launch structure at this point. The dashed line on Figures 4 to 6 indicates this limit for the experimental trials. The setback in the simulator trials was not limited. Some differences in the setback measures are observed on the upslope near the trough of the wave (30 to 60 degrees) when the wave height is 6 m and there is a close match with most phase angles when the wave height is 10 m. As indicated in Figure 5, the measured setback for the simulator continued to increase above 11 m as the vessel was launched closer to the trough (0 to 30 degrees) as the launces were not limited by collisions.

Figure 6 shows the setback vs. wave height (H_w) for specific waves for both the simulator and experimental measures. The solid line indicates the values where setback is double the maximum wave height. The experimental outcomes showed maximum setback is approximately double the wave height up to a wave height of 6 m (Simões Ré et al., 2002). At higher sea states this could not be confirmed in the experimental results due to the impacts of the evacuation craft with the structure. The increase in setback from the simulator tests followed a similar trend line, with some occurrences of setback above the prediction for the 6 m wave height. The trend of increasing setback and variability in setback with increased wave height is consistent between the simulator and experimental measures.

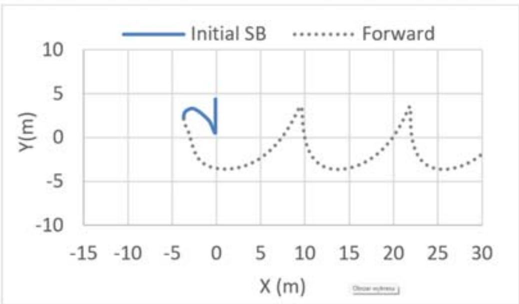

Figure 8. Simulator XY Trajectory - Launch near wave crest: H_w = 7m, T = 9m

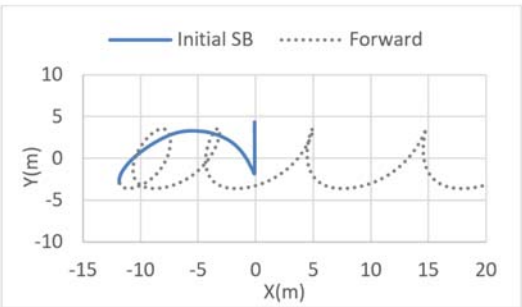

Figure 9. Simulator XY Trajectory – Launch near wave trough H_w = 7 m, T = 9

Trajectory comparisons were made between the experimental cases and the simulator to ensure vessel kinematics were similar. A key focus was the observed behaviour of the vessel when it was launched on different positions between the crest or trough of a wave. A sample of the validation case is discussed. Figures 8 and 9 are sample runs from the simulator showing the trajectory of the vessel on launch and sail away. Figure 8 shows the vessel setback was lower when the vessel was launched near the crest of the wave, and the vessel was able to continue forward steadily with each wave encounter. With large vessel setback, as in Figure 9, the vessel had to first overcome the backwards motion. The vessel progressed more slowly, with some progressive setback on the initial wave encounters, and then was able to continue forward with additional wave encounters. Similar behaviour was observed in the experimental studies.

In summary, the comparisons indicate the virtual wave tank provides measures that are representative of the vessel and wave interactions seen in the experimental studies. The amount of setback with wave height and the change in setback with position of launch on the wave (crest or trough) were consistent with the experimental studies. The motion of the vessel on water entry and sail away in the simulator was also representative. Differences between the measures can be attributed to differences in scaling, variability in physical observations compared to numerical simulations, and differences in limitations between the experimental test setup and the simulator.

5.2 *Results: Investigation 1 – study of individual wave setback in high sea states, regular waves*

A summary of the setback measures for each set of launches is provided for each of the regular waves studied. The measured setback for each launch is also related to the launch position on the wave (phase angle). In effect, this data set provides an extension to the outcomes presented in the scale model experiments, with the outcomes extended to higher wave heights.

Table 5 provides a summary of the setback measures for launches performed for each wave height tested, from 2 m to 14 m. Summary data includes the average setback (Avg. SB), the median of the measured setback (Med.), and standard Deviation (SD) for each set of 48 launches performed for each wave height. The 90th percentile (90th PER.) of measured setback is provided to indicate the higher measures in the data set for each sea state.

The outcomes indicate increasing setback with increase in wave height, with the average setback increasing from 3.23 m in a 4 m wave height to over 30 m in a 16 m wave. The measures indicate setback as high as 65.9 m in a 16 m wave. There is also higher variability in the setback as wave heights increase, which is consistent with previous studies. For all wave heights, the median was lower than the average setback, indicating there were a higher number of low setback measures for each set of launches. Figure 9 shows a graphical summary of this information in a box plot.

Table 5. Setback Summary - Regular Waves

H_w (m)	4	6	8	10	12	14	16
Avg. SB(m)	3.23	5.82	8.47	10.1	14.1	20.0	30.4
Med.	2.85	3.75	6.05	6.31	9.11	14.0	28.2
SD 90th	2.99	4.68	6.83	8.98	13.1	17.0	22.4
PER.	7.23	13.0	17.8	24.3	36.3	45.6	62.4
Max SB(m)	9.1	14.9	25.1	28.0	42.7	54.5	65.9

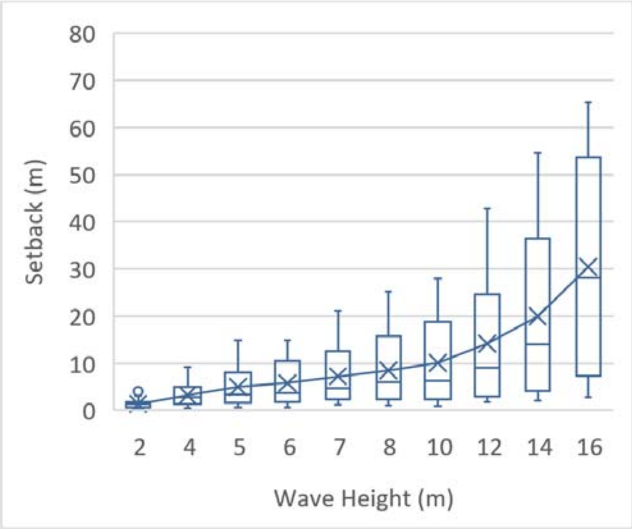

Figure 9. Vessel Setback, Regular Waves

Figure 10 shows the setback values and phase angles for each set of simulated launches in the higher wave heights, from 10 m to 16 m. The results indicate that the splashdown occurs most frequently between 0 and 90 degrees, with few occurrences of launches outside of this range when the wave height is greater than 8 m. Analysis of the setback and wave angle for higher wave heights shows the maximum setback increased significantly when the vessel was launched closer to the trough of the wave (0 to 30 degrees). Low setback values are possible when the boat is released closer to the crest of the wave (60 to 90 degrees). The results are similar to the outcomes of previous research (Simões Ré et al., 2002).

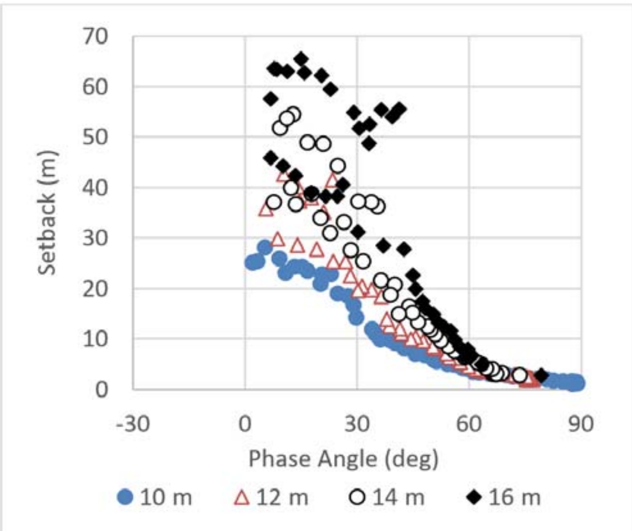

Figure 10. Setback vs. Phase Angle, Regular Waves

Figure 11 shows the percentage of launches with greater than 20 m setback. As indicated in this figure, in wave heights of 10 m or greater, the number of occurrences increases with wave height, with over 50% of the launches in a 14 m wave meeting this criterion. Figure 12 shows the percentage of launches that required greater than 60 s clearance time (%Cleartimes>60s). For wave heights of 10 m and above there were observed cases where the vessel could not exit the launch location in less than 60 s, with occurrences increasing as wave height increases. The vessel was able to evacuate and reach 20 m from the launch position in less than 60 s for all launches performed in 8 m wave height or less.

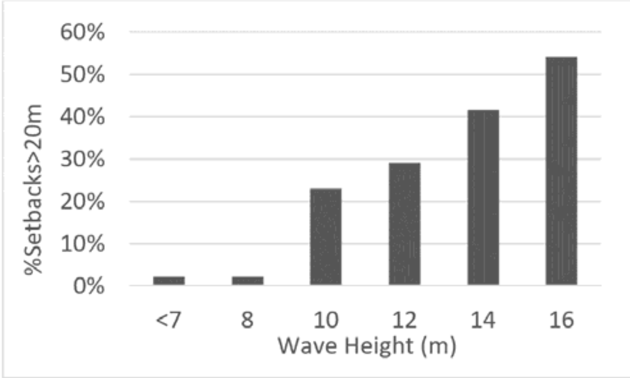

Figure 11. Setback Occurrences Greater Than 20m, Regular Waves

The results show that in wave heights of 12 m or above the number of cases where the vessel was not able to exit the evacuation zone increased, as indicated by the Failed Clearances series in Figure 12. For 50% of the launches performed in a 16 m wave height the vessel was unable to exit the evacuation zone. This outcome indicates a limit of the lifeboat in this high sea state. The outcomes again showed an increase of occurrences with increasing wave height.

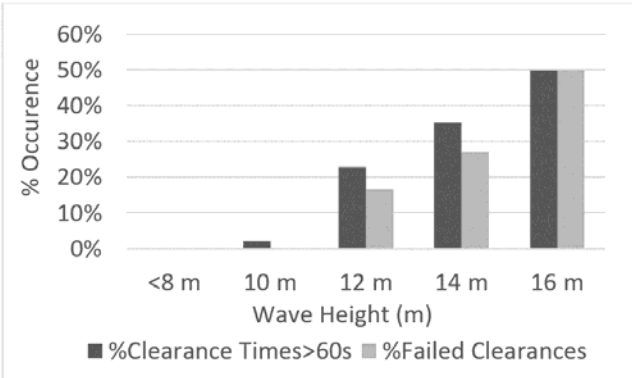

Figure 12. Clearance times Greater Than 60 s and Failed Clearances, Regular Waves

Investigation of the trajectories highlights that the maximum setback in high sea states can be a result of continued progressive setback. Figures 13 to 15 present samples of the XY trajectory for a vessel launch in the three highest wave heights. For each plot, the launch position on the wave is the same for each wave height and is near the trough of the wave. In the 12 m wave, the vessel was setback initially and was able to progress forward after 2 wave encounters. In a 14 m wave, the initial and progressive setback set the vessel back further and the vessel was still able to start moving forward after two wave encounters. For the 16 m wave, the wave and wind forces continued to push the vessel backwards, and the lifeboat was unable to move forward. This outcome indicates a limit has been reached, and there is not enough propulsion force to overcome the wave and wind forces. As noted, there were cases in the data sets for both 12 and 14 m waves where the vessel was not able to exit the evacuation zone, indicating that the combination of initial setback and continuous wave and wind forces resulted in a limit being reached in these sea states. These cases relate to the launches with high setback shown in Figure 9, which occurred when the vessel was launched near the trough of the wave (0 to 30 degrees).

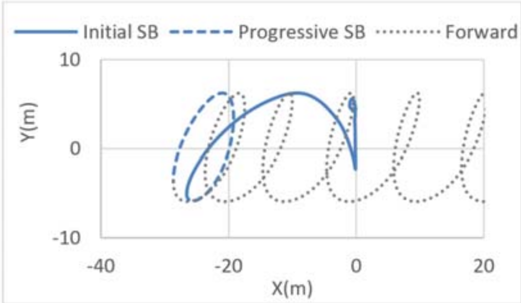

Figure 13. Vessel Trajectory H_w = 12 m, Regular Waves

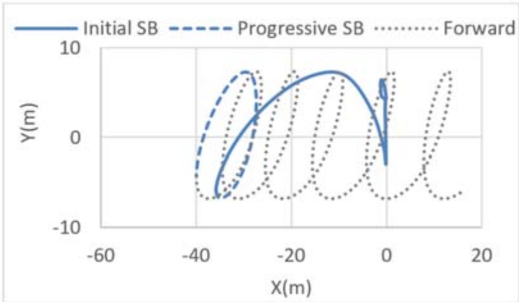

Figure 14. Vessel Trajectory H_w = 14 m, Regular Waves

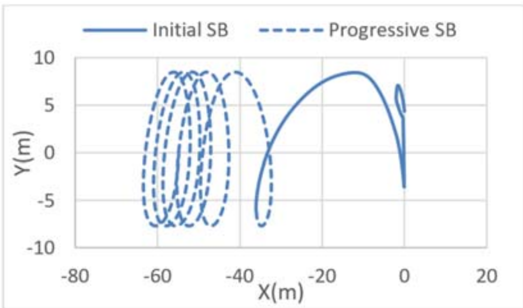

Figure 15. Vessel Trajectory H_w = 16 m, Regular Waves

5.3 *Results: Investigation 2 – study of lifeboat performance in irregular 100yr seas*

For irregular seas, setback is again analysed for the sets of launches for each wave height. The percentage of occurrences with clearance time greater than 60 s and failed clearances is also discussed.

A summary of the setback measures (Avg. SB, Med., SD, 90th PER.) is provided for each set of the 144 launches performed for each wave height. Table 7 summarizes the setback measures of the lifeboat in the irregular seas tested, with Hs from 6m to 12 m. The average measured setback for each set of launches increases with increasing sea sate. The 90th percentile is again provided to indicate the higher measures in the data set.

The 90th percentile indicates there were occurrences with setback above 20 m for an 8 m wave height, with setback values above 37 m and 50 m in 10 m and 12 m waves, respectively. The standard deviation of the data increased with wave height indicating higher variability in the measured setback as wave height increases. The median of the measured setback for each sea state remained low and below the mean, with a skew towards lower values. This outcome indicates that there were still a higher number of low setback values for each set of launches, similar to the tests performed in regular seas.

Table 6. Setback Summary - Irregular Seas

Hs (m)	6	8	10	12
Avg. SB (m)	6.36	8.94	12.99	17.16
Med.	4.60	5.80	5.84	7.07
SD	5.31	8.40	15.35	21.49
90th PER	6.23	21.85	37.01	51.20

Figure 16 provides a breakdown showing the percentage of occurrences for measured setback. Ranges of setback values are grouped to summarize the data. The figure indicates the over 50% of launches resulted in less than 10 m setback for each of the wave heights tested. Impact with the launch structure is unlikely in these cases. The percentage of launches with setback less than 10 m decreased from 78% in a 6 m wave height to 59% in a 12 m wave height. Over 74% of all test cases resulted in less than 20 m setback. Above 20 m, contact with the launch platform is more likely, as discussed in the performance measures. The percentage of launches with greater than 20 m setback was 16% in a 10 m wave height and 25% in a 12 m wave height. In 10 m waves, setback greater than 40 m occurred in 8% of test cases, increasing to 16% in a 12 m sea. This result indicates high setback values are possible in these extreme seas.

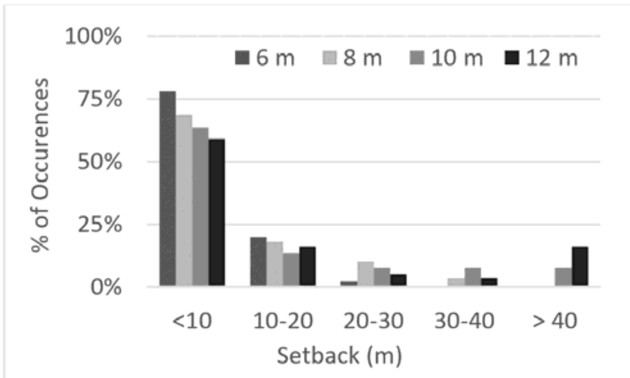

Figure 16. Setback Occurrences, Irregular Waves

Figure 17 shows the breakdown of the times to reach the target 20 m distance for a clearance. In most cases, the vessel was able to reach the target distance in less than 60 s. The results also indicate that in 8, 10 and 12 m wave heights there were several cases where the vessel was unable to reach the target distance of 20 m required for clearance, as indicated by the Fail series in Figure 17. In an 8 m significant wave height, in 13% of the simulations resulted in a failed clearance. 35% of cases performed in a 10 m sea resulted in a failed clearance, increasing to 41% in a 12 m wave.

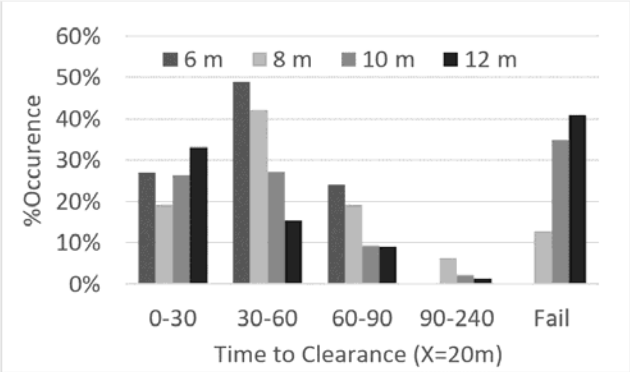

Figure 17. Time to Clearance, Irregular Waves

Figure 18 shows the sample trajectory of the lifeboat in a 10 m Hs where initial launch position close to a trough results in high initial setback. The lifeboat was initially setback over 20 m, and experienced progressive setback for 2 wave encounters resulting in a further setback of ≈ 8 m. The vessel was then able to progress forward. An additional 5 wave encounters occurred before the vessel could return to the launch position. For this case it took approximately 56 seconds for the vessel to progress from the maximum setback point to the original launch position. Figure 19 shows the vessel trajectory in a 12 m Hs and a launch near the trough of the wave. The vessel experienced initial setback of approximately 25 m and additional wave encounters set the vessel back further to close to 50 m. The vessel was not able to start forward progress. This result indicates a limit has been reached. These examples are provided to show a case where high initial setback occurred due to location of launch on the wave and was then not able to progress forward and another where the vessel could not overcome the environmental forces. As noted, cases were observed in both 10 m and 12 m wave heights where the vessel was unable to exit the escape zone due to progressive setback.

These outcomes show there is a higher likelihood of encountering a hazard if sea states are higher than 10 m. The combination of high setback and progressive setback can result in possible impact of the vessel with the launch structure or the inability to exit to a safe area. In wave heights of 8 m or less, the setback was reduced but not eliminated.

The results also indicated that most of the launches resulted in low setback even in higher sea states. For all the wave heights tested the median of the setback measures is less than 7 m and most of the launches resulted in setback less than 10 m. For the highest sea state tested (Hs = 12 m), the time to evacuate was less than 60 s for 48% of the launches. This percentage was higher for lower sea states. This result shows that successful launches can occur in the highest waves tested if the vessel avoids launching on a wave position that results in high initial setback.

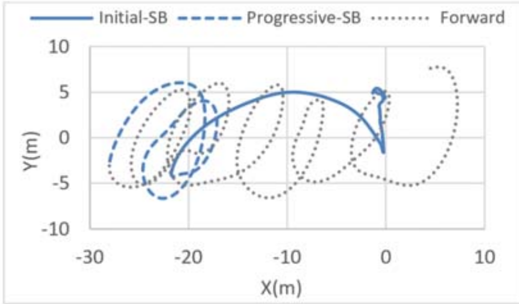

Figure 18. Vessel Trajectory, Hs=10m, Irregular Waves

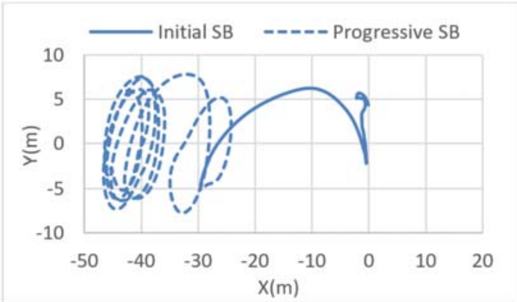

Figure 19. Vessel Trajectory, Hs=12m, Irregular Waves

5.4 *Results: Investigation 3 – study of human performance on evacuation performance in irregular 100yr seas*

This section discusses the impact of 1) a delay in throttle, 2) a delay in hook release and 3) cases where the throttle is applied prior to hook release. For each of these cases, 144 launches were performed for each wave height tested. A summary of the setback measures for each set of launches performed for each wave height is provided. The percentage of occurrences with greater than 20 m setback, clearance times greater than 60s, and failed clearances are discussed. Comparisons are made to the data from the second investigation where there was no delay in throttle or time to hook release.

5.4.1 *Delay in Throttle*

Table 7 presents the summary of the setback measures for sets of launches performed with a 2 second delay (TT2) and a 4 second delay (TT4) in time to applying throttle after hook release. Figure 20 shows a comparison of average setback measures for each sea state, with comparison made to no throttle delay (TT0).

The results show that there was an increase in average setback of approximately 17% over all wave heights when time to throttle is delayed by 2 s, compared to the set of launches when there was no throttle delay. There was an average setback increase of 35% when the time to throttle was delayed by 4 s. Similar to the previous investigations, the median of the setback measures was below the average setback for each wave height, indicating a high number of low setback cases for each set of launches. The increase in the 90th percentile of measured setback for each of the wave heights shows the increased throttle delays resulted in higher setback measures.

Table 7: Setback Summary – Delayed Throttle, Irregular Waves

Average Setback (m)				
	6 m	8 m	10 m	12 m
TT0	6.36	8.94	12.99	17.16
TT2	7.12	10.75	15.37	19.91
TT4	7.95	15.77	15.94	20.75
Median (m)				
	6 m	8 m	10 m	12 m
TT0	4.56	5.73	5.73	7.06
TT2	4.59	5.91	5.62	7.39
TT4	4.72	6.03	6.30	8.88
90th Percentile (m)				
	6 m	8 m	10 m	12 m
TT0	14.74	21.86	37.01	51.20
TT2	17.18	25.61	38.64	54.91
TT4	19.31	27.24	39.77	54.17

Figure 21 shows the percentage of occurrences of setbacks greater than 20 m increased an average of 4% for TT2 and 7% for TT4, compared to no throttle delay. The percentages increased to over 20% in an 8 m wave and to over 30% in a 10 or 12 m wave when throttle was delayed 4s. As shown in Figure 22, with a delay in throttle of 2 s, the measured occurrences with clearance times greater than 60 s increased by 11% in 10 m waves and by 12% in 12 m waves. Related to this outcome, the increased throttle delays resulted in more occurrences of the vessel being unable to leave the clearance zone, as shown by the Failed Clearances in Figure 23. In a 12 m wave, delayed throttle by 2 or 4 s resulted in the vessel not being able to exit the evacuation zone in over 40% of the launches.

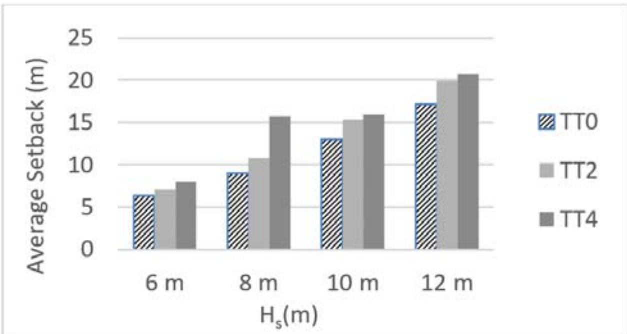

Figure 21. Average setback, Delayed throttle, Irregular Waves

Relating this to operational objectives, the results suggest the target is to apply throttle as quicky as possible following hook release. It is unrealistic to assume a coxswain will be able to release the hook with no delay though applying the throttle in less than 2 s is achievable, as observed in training courses. Training should provide sufficient practice for trainees to learn to operate the hook release as quickly as possible. Training scenarios can also incorporate plausible outcomes identified in this study. If during training coxswains are observed to take a long time to apply throttle then there is a possibility of a collision or inability to evacuate the launch area. These outcomes can be built into simulator scenarios to provide feedback.

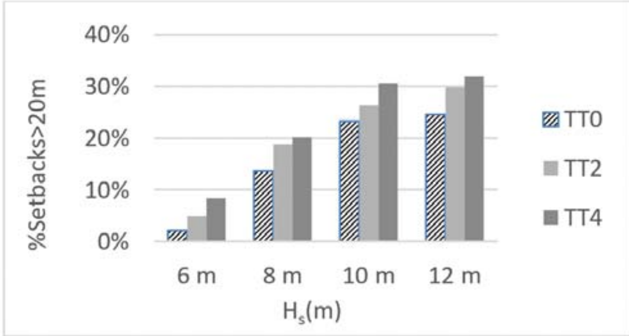

Figure 21. Setback Occurrences >20 m, Throttle Delays, Irregular Waves

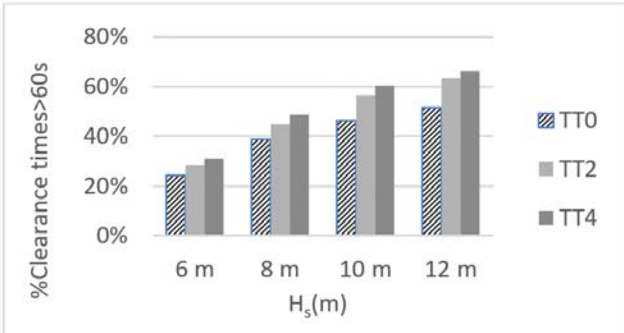

Figure 22. Clearance Times Greater Than 60 s, Delayed throttle, Irregular Waves

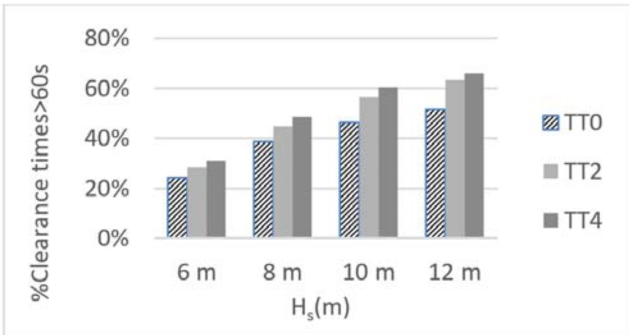

Figure 23. Failed Clearances, Delayed Throttle, Irregular Waves

5.4.2 *Delay in Hook Release*

Table 7 shows the summary of the setback measures for each of the sets of launches performed with a 2 second delay in time of hook release (TR2) and a 4 second delay in releasing the hook (TR4). Comparisons are again made to an instant time to hook release and throttle (TT0-TR0).

Table 8 and Figure 24 indicate an initial reduction in average setback and occurrences of setback greater than 20 m when the hook release delay was 2 s (TR2), and then an increase in these values when the throttle delay was 4 s (TR4). The occurrence of clearance times greater than 60 s also changed, with a reduction the percentage of occurrences for TR2 and an increase in TR4. A considerable increase in occurrence of clearance times greater than 60s and failed evacuations occurred in a 12 m wave height, with 74% of the cases resulting in failed clearances. These outcomes are shown in Figures 25 and 26.

Table 8. Setback Summary, Delayed Hook Release, Irregular Waves

	6 m	8 m	10 m	12 m
Average Setback (m)				
TT0	6.36	8.94	12.99	17.16
TR2	5.53	6.39	8.02	8.02
TR4	9.49	11.05	17.57	17.57
Median (m)				
TT0	4.56	5.73	5.73	7.06
TR2	4.84	5.54	6.94	7.06
TR4	5.58	7.07	9.79	20.1
90th Percentile (m)				
TT0	14.7	21.9	37.0	51.2
TR2	8.59	10.3	11.4	27.3
TR4	23.3	25.4	43.5	57.0

While these outcomes seem counterintuitive, the behaviour can be explained by considering how the delay in hook release affects the position of release on the wave. Given the wave shape and slope, the vessel is likely to land on the upslope of the of the dominant wave (0 to 90 degrees), as indicated in previous research (Simões Ré et al., 2002) and Investigation 1 of this paper. The delay in hook release keeps the lifeboat in position, and the fall wires do not extend enough for the vessel to drift backwards significantly. As a result, for a small delay the vessel could release on the top or the downslope of the wave where wave forces were more favourable to reduce setback. Too long a delay resulted in both the vessel starting to drift backwards and release occurring closer to a trough of the wave where wave forces could induce more setback. In effect, delay in hook release provided a short window of benefit and the "wave shadowing" was reduced for a short time.

This window is expected to be highly dependent on wave shape (height, period, and steepness). The results are specific to the wave shapes used in this study. Further investigation is required to determine if similar outcomes are seen in different wave shapes, which is outside of the scope of this paper.

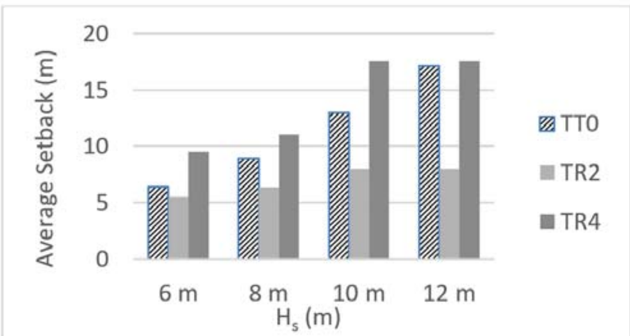

Figure 24. Average Setback - Delayed Hook Release, Irregular Seas

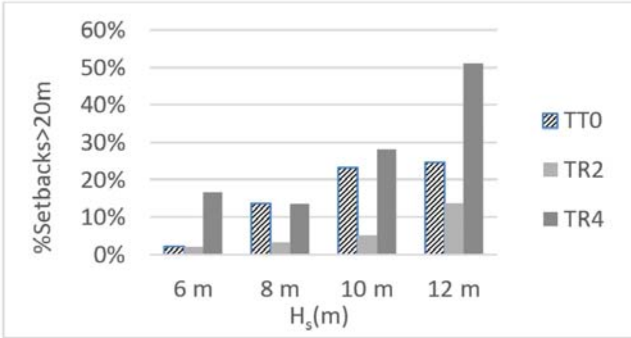

Figure 25. Setback Occurrences > 20 m, Hook Release Delays, Irregular Waves

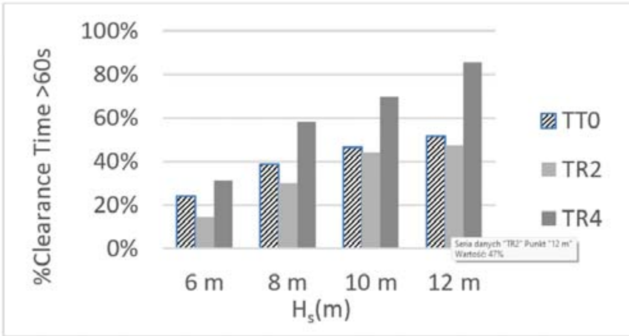

Figure 26: Clearance Times Greater Than 60 s, Hook Release Delays, Irregular Waves

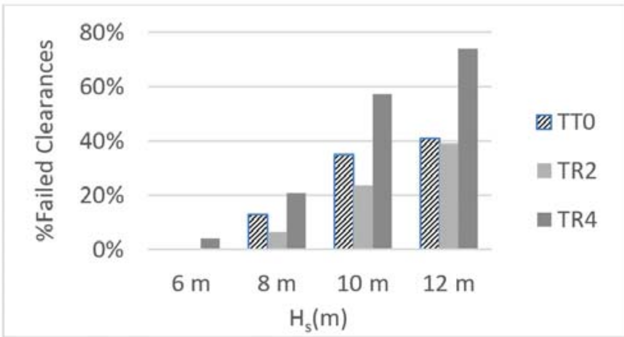

Figure 27. Failed Clearances, Hook Release Delays, Irregular Waves

5.4.3 *Throttle Before Hook Release*

The following cases summarize the measures from launches where the throttle is applied prior to the release of the hooks. As noted in the methodology, the times presented are relative to the time the vessel was able to be released (t = 0) and the timing was varied for the time to throttle (TT) and time to release (TR) of the hooks. In these cases, the lifeboat remained tethered and propulsion force was applied before the hook was released. Comparisons are made with the case where throttle and hook release were applied immediately (TT0-TR0).

As indicated in Figures 28 to 30, there was an improvement in most outcomes when throttle was applied early and prior to the hook release. The greatest improvement in all performance measures occurred when the throttle was applied 1 s after the vessel could be released and the hook was released 1 s later. This series is noted as TT1-TR2. As indicated in

Figure 28, Average setback was reduced by approximately 50% and there was a reduction of setback occurrences greater than 20 m and clearance times greater than 60 s. Similar outcomes were observed for cases TT1-TR3 and TT2-TR3. For these cases, the percentage of setback occurrences greater than 20 m was reduced to 10% or less in all wave heights tested, as indicated in Figure 29. These results indicate that application of throttle before hook release creates enough initial propulsion to improve launch performance based on the measures discussed.

The results indicate that the timing of throttle before hook release must still be performed quickly, and hook release cannot be delayed too long. This is shown in the case where the time to throttle was performed 2 seconds after the vessel is able to be launched and time to hook release was performed two seconds following (TT2-TT4). Figure 28 indicates a small increase in average setback in high sea states for this case. Figure 29 shows there were increased occurrences of setback greater than 20 m in a 12 m wave height. Figures 30 and 31 show there was an increase of occurrence of clearance times greater than 60s and failed clearances in 10 and 12 m wave heights. This result again suggests that high throttle and hook release delays can result in reduced performance.

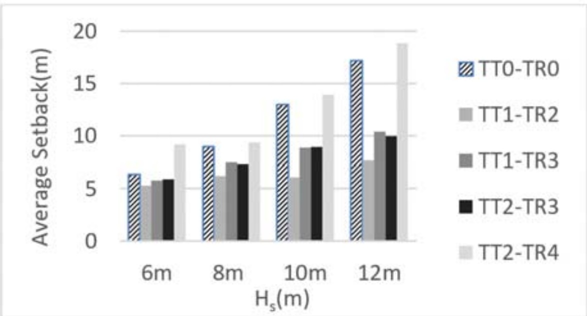

Figure 28. Average Setback, Throttle before hook release, Irregular Waves

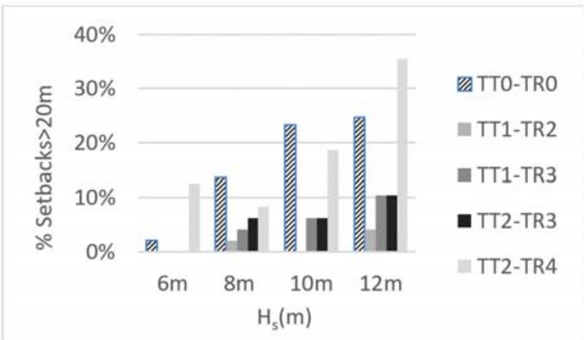

Figure 29. Setback Occurrences Greater Than 20 m, Throttle Before Hook Release, Irregular Waves

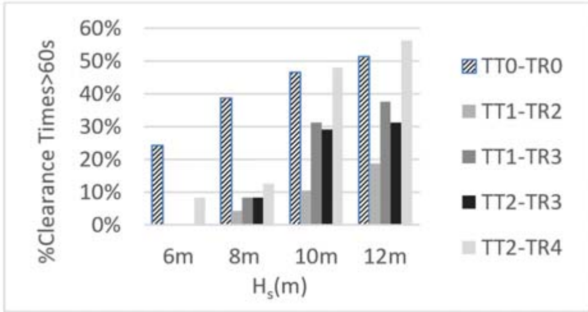

Figure 30. Clearance Times Greater Than 60 s, Throttle Before Hook Release, Irregular Waves

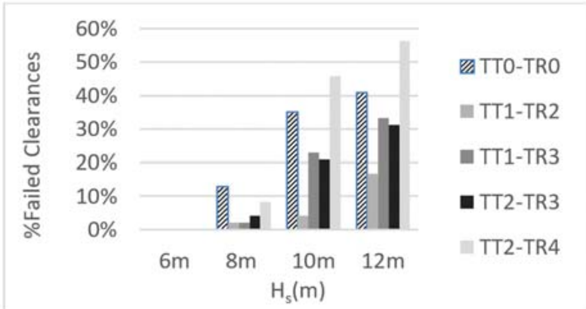

Figure 31. Failed Clearances, Throttle Before Hook Release, Irregular Waves

These cases show a procedure that can be performed to give the vessel initial propulsion prior to being released. The results show better launch performance when throttle is applied before the vessel is released. The results indicate a need for these actions to be performed in a timely manner.

6 CONCLUSIONS

The goals of the research were to use simulation to extend the knowledge of lifeboat performance in high sea states and to evaluate how human performance can affect outcomes.

The results show a strong relationship between the performance measures and wave conditions. Specifically, both setback and time to exit the launch area were both dependent on wave height and the wave phase angle at the launch point. These results are the same as found previously in experimental work up to about 10 m (Simões Ré et al., 2002), but have extended the wave heights up to 16 m in the simulation environment.

The position on the incoming wave at which the lifeboat was launched (i.e. the wave phase angle) was found to be particularly important. When launched at or very near the crest, lifeboats avoided large setback and were able to make way relatively quickly to clear the launch zone. Conversely, when launched near the trough or the upslope of the incoming wave, the lifeboats were setback immediately by the wave. The magnitude of the setback was dependent on wave height in addition to wave phase angle. Consequently, the initial setback experienced by the lifeboat during its first wave encounter made clearing the launch more difficult for two reasons: first, the lifeboat had to overcome the momentum associated with the setback action; second, its effective starting point was behind the nominal launch target (directly below the davits) by a distance equal to the setback (or progressive setback).

In practical terms, one consequence of setback is that the lifeboat can collide with the launch platform if there is insufficient clearance between the launch target and the platform. While the environmental conditions at the time an evacuation are outside the control of evacuees, the timing of the launch is not. Timing a launch requires that the coxswain can see or otherwise sense the approaching waves and has enough familiarity with the lifeboat controls (e.g. lowering, releasing the hooks, throttling) to perform the launch operation within the narrow time window required for a successful launch on a crest. For a typical large wave, the window for a crest launch is only about 5 to 7 seconds.

The studies of time of throttle delay and time of hook release timing provide insights on how human actions can affect launch performances. Interpreting the outcomes of the third investigation, we see a general trend that a quicker performance of actions results in better performance outcomes. This result has implications for training. Delays in actions can be due to inability to recognize launch cues (i.e. the hydrostatic indicator movement), improper movement of the hook release handle, or performing actions out of order. These timings can be further delayed if there are faults in the system that require additional time to remedy, such as performing a hydrostatic override procedure. The results of this research suggest training goals should target the quick performance of these actions and training to provide practice to improve these timings.

The research also indicates that new operational procedures can improve launch performance. Applying the throttle prior to hook release can reduce setback and escape times significantly, as long as these actions are performed quickly. This procedure was suggested by operators with marine experience. Operational procedures that result in improved performance can be embedded into curriculum to train coxswains.

Considerations must be given to the specificity of the wave environments and launch configuration when interpreting the research outcomes in this paper. As indicated in previous research (Simões Ré & Veitch, 2004), the wave steepness can have a considerable effect on the amount of measured setback, although wave steepness was not varied in the current work. The simulations focused only on escape from the platform in a head sea where wave direction is directly against the desired escape path of the launch vessel. This scenario was considered as a worst case. Scenarios with oblique waves and winds would present additional operational challenges (e.g. maintaining a desired heading).

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