TECHNICAL NOTE

THE TRANSIENT EFFECTS OF FLOOD WATER ON A WARSHIP IN CALM WATER IMMEDIATELY FOLLOWING DAMAGE

G J Macfarlane and **M R Renilson,** Australian Maritime College, University of Tasmania, Australia
T Turner, Defence Science & Technology Organisation, Australia
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SUMMARY

The safety of a ship which is damaged below the waterline will depend on the way water floods into the internal compartments. The water will cause the ship to take on an angle of heel and trim which will further affect the flooding into the compartments. The ship's equilibrium position in calm water can be predicted using hydrostatic theory, however at present it is difficult to predict the transient behaviour between the initial upright position of the ship and its final equilibrium. In some cases, the transient motion may cause a capsize prior to a possible equilibrium position being reached.

This paper describes an investigation of this phenomenon using a model of a warship with simplified, typical internal geometry. With the model initially stationary, a rapid damage event was generated, and the global motions measured, along with the water levels in some of the internal compartments, as functions of time. Immediately after the damage occurred the model rolled to starboard (towards the damage). It then rolled to port (away from the damage) before eventually returning to starboard and settling at its equilibrium value. In all the tests conducted the equilibrium heel angle was less than that reached during the initial roll to starboard. This implies that the roll damping, and the way in which the water floods into the model immediately following the damage, could both have a very important influence on the likelihood of survival.

1. INTRODUCTION

When a ship suffers damage below the waterline water will flood into the internal compartments that have become open to the sea. This will result in it taking on an angle of heel and trim. In extreme cases it may result in capsizing or sinking of the ship (Turner *et al.* 2010).

Although the equilibrium position in calm water can be calculated using traditional hydrostatic theory, the transient behaviour which occurs between the initial position of the ship and its final equilibrium may cause a capsize where static theory suggests that the vessel would survive. In addition, the dynamic effects during the transient phase may allow additional water to enter through the hull opening, resulting in a different equilibrium position to that obtained from statics alone.

In order to investigate this behaviour for a warship with a complex internal geometry, model experiments were conducted in the Model Test Basin at the Australian Maritime College (AMC) on a model of a generic destroyer hull form (Macfarlane and Renilson, 2010, Ypma and Turner, 2010). The tests were sponsored by the Cooperative Research Navies group (CRN) to assist in validating the accuracy of the flooding model used in a non-linear time domain code, FREDYN.

2. MODEL DETAILS

A 3.268 metre long model (LOA) of a generic destroyer was constructed and fitted with a removable perspex module containing an arrangement of the internal compartments, which, although not as intricate as that of a full scale ship, has the necessary complexity to be used to investigate the phenomena associated with progressive flooding. The scale factor was 1:45.

The principal particulars of the model are provided in Table 1. The profile and body plan of the model are shown in Figures 1 and 2, respectively. A photograph of the model is shown in Figure 3. The model was fitted with bilge keels and fixed stabiliser fins as shown in Figure 4.

The model was fitted with four transverse bulkheads with the two end bulkheads made watertight to contain the flooding. The following tanks and deck levels were also modelled:

- simplified tanks
- simplified 2nd Deck
- simplified 1st Deck

The layouts of the compartments for each deck level are provided in Figure 5(a, b and c). The designation for each compartment is given in these figures. All hatches and doors shown in these figures remained open throughout the duration of the test program. Cross sections at the locations AA, BB and CC indicated in this figure are provided in Figure 6(a, b and c). The approximate locations of the four transverse bulkheads (B1, B2, B3 and B4) are indicated on the profile of the model, shown in Figure 1. Further details about the model and test procedure are provided in Macfarlane and Renilson, 2010.

A rectangular shaped damage opening was located on the starboard side of the ship model. When intact, this opening was sealed using a taut latex membrane.

A very rapid damage opening scenario was simulated by puncturing the taut membrane using blades attached to a pneumatic ram that was operated by a remote switch. Puncturing the membrane in this way resulted in the loss of the latex patch within $1/25^{th}$ second (one video frame), leading to a very rapid damage event.

3. EXPERIMENTAL SET UP

3.1 INSTRUMENTATION

The water surface elevation within specified tanks was measured using wave probes. A total of seven wave probes were included to measure the water levels in the following compartments: 0Fwd-S06; 2Aft-S11; 2Centre-S12; 2Centre-S15; 1Aft-S17; and 1Centre-S23. The locations of these are indicated on Figure 5 by: 'WP'. Two video cameras were deployed; one internal camera located onboard the ship model to view the flooding of the compartments and one external camera to view the entire model.

The motion of the fully unconstrained model was measured in all six degrees of freedom by a non-contact digital video tracking system (Qualisys). The calibration of this system utilises a series of 16 permanent reference markers that have been surveyed into position around the basin. The capabilities and operation procedures of this system are described in detail in Qualisys (2008). A set of active markers were installed on the model to allow the Qualisys system to track the model's motion. These four white spherical markers can be seen in Figure 3.

3.2 UNCERTAINTY

The following levels of uncertainty were estimated:

- Model dimensions = breadth and draught ±1.0 mm and for length ±1.5 mm
- Model displacement = ±100 grams
- Model KG = ±1.0 mm
- Model roll radius of gyration = ±3.0 mm
- Model pitch radius of gyration = ±2.0 mm
- Water surface elevation = ±2.0 mm
- Measurement of roll and pitch = ±0.1 degrees

3.3 TEST PROCEDURE

For all the runs the model was in calm water and at zero forward speed. The water depth in the basin was monitored daily and fixed at 800 mm.

Prior to the commencement of each test run approximately 3 seconds of data was collected while the system was static. This provided a 'zero' position for each instrument which was subtracted from the data to provide absolute values. For the Qualisys system, recording of the model motions was triggered to coincide with the recording of the wave probe data.

On completion of data acquisition the model was removed from the basin, the water was emptied from all tanks and carefully dried and a new latex membrane fitted over the damage opening prior to setting up for the next run. Once the model was prepared and located, the basin was allowed to return to a calm state before the next run was begun.

4. TEST PROGRAM

Five runs were conducted to determine the repeatability of the process, and three additional runs were conducted at different KG values to investigate the effect of KG on the results. Note that only valid runs of relevance to this work are reported here.

5. RESULTS AND DISCUSSION

5.1 REPEATABILITY

A comparison of the results from five runs with the same nominal particulars gives a good indication of the repeatability of the process. In this case the KG remained constant at 173mm.

The results from these runs are compared in Figures 7 to 13. Note that in all cases time t = zero seconds is the point at which damage has been initiated.

It should be noted that all results are given in model scale.

5.1(a) Roll angle

The roll angle as a function of time for each of these runs is shown in each of the plots (right axis), as well as in Figure 7. As can be seen, for each of these runs the damage causes an initial positive heel angle (to starboard), followed by a negative heel angle (to port) and finally the model rolls back to starboard again and settles at its equilibrium heel angle without an overshoot.

The initial motion is very similar for all the runs, with the initial heel angle to starboard being almost the same for all five runs. Even the small unsteadiness in the roll as the model starts to roll back to the upright is similar in all these runs. However, the extreme angle to port (away from the damage) is different in the five different runs, and the roll angle as a function of time from that point onwards is different, until the model finally settles at approximately the same equilibrium angle to

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starboard. During this period, differences in roll angles at the same time of up to about 4º occur. The equilibrium heel angles generally agree with that predicted using hydrostatic software.

It is noticeable that runs P1_R14, P1_R15 and P1_R28 have similar extreme port roll angles, and exhibit a similar behaviour, whereas runs P1_R12 and P1_R16 have a similar extreme port roll angle which is different to the other three runs.

Of interest is that the maximum roll angle in the initial phase is greater than the final equilibrium roll angle. As the initial roll angle will be dominated by the roll damping, and the way in which the water floods into the model immediately following damage, both could have a very important influence on the likelihood of survival. For example, if the initial heel angle exceeds the angle of vanishing stability in the damaged condition, the model will capsize.

5.1(b) Pitch Motions

The pitch motions for the five runs are plotted as functions of time in Figure 8. Note that the roll angle for each run has also been included in this figure (right axis), to assist with the interpretation of the pitch motions. There is very little difference in pitch for the first 10 seconds after damage initiation, with a small difference occurring after that, before the model reaches a similar pitch angle for each of the runs.

5.1(c) Water levels in compartments

The water levels at the wave probes for each of these runs are plotted as functions of time in Figures 9 – 13, along with the roll angles for each of these runs. Note that as the water level did not reach the wave probe in the 1st deck on the port side in the centre compartment (1Centre-S23) in any of these runs, the results from this probe are not included.

As can be seen, there are differences in the water levels for each of these runs, although the final equilibrium values are similar. In general, the first few seconds after the damage initiation showed very similar results, with any deviations occurring after about 8 seconds following the damage event, corresponding to where the roll angles also differed between runs.

The water level in the only bottom tank where the level was measured (0Fwd-S06 – Figure 9) shows initially similar results for the different runs, however the time for the final equilibrium to be reached is different. This may be due to the way that the air exited the tank, with clear vortexes forming in some cases. The reason that this tank did not fill completely is that some air was entrapped, preventing the water from rising further at the inboard (upper) edge of the tank where the wave probe was located.

The water level in the centre tank on the starboard side close to the damage on the 2nd deck also showed little difference initially between the five runs (2Centre-S12 – Figure 10). The later differences correspond to differences in roll angle. This probe is fully submerged upon reaching the equilibrium position in all five runs.

The water levels at the wave probes on the 2nd deck at the port side both showed what appeared to be two different phenomena, with runs P1_R12 and P1_R16 exhibiting one behaviour, and runs P1_R14, P1_R15 and P1_R28 another behaviour, as seen in Figures 11 and 12. For water to reach either of these wave probes it had to pass right across the model, and through openings in both the port and starboard longitudinal bulkheads (see Figure 5b).

The two different patterns of behaviour in the water level for these two compartments exhibited by runs P1_R12 and P1_R16 compared to the behaviour exhibited by runs P1_R14, P1_R15 & P1_R28 also corresponded to the difference in roll angle behaviour noted above.

Finally, the water level on the aft bulkhead in the aft compartment on the starboard side (1Aft-S17) did not rise until well after the damage was initiated, and the model was heeling to starboard, close to its equilibrium position (Figure 13). For each of the runs the time that the water level reached the wave probe was slightly different, however the rate of rise of the water level was similar, as was the equilibrium value.

5.2 EFFECT OF KG

A number of runs were conducted with different vertical centre of gravity (KG) positions as given in Table 2. The roll radius of gyration was only measured for the single case of KG = 173mm (where k_{xx} = 140mm), however, it is believed that this value would have varied by less than 8% for the other KG configurations.

The results are plotted as functions of time in Figures 14 – 18. For clarity, the results from only two of the five runs with a KG value of 173 mm are included. These approximate to the two extreme values for that condition.

5.2(a) Roll angle

As can be seen in Figure 14, the runs with the higher centre of gravity positions result in a greater initial heel angle, a greater intermediate heel angle to port, and a greater equilibrium heel angle. For the lowest KG value tested, the model does not heel to port during the run, although the starboard heel angle is reduced after the initial value, before increasing to the equilibrium value. This demonstrates the importance of changes in

KG to the dynamic aspects of the motion after damage, as well as the final equilibrium value.

Note that for run P1_R08, with a KG value of 163 mm, the model had an initial heel angle of about 0.7º to starboard, which was assumed to be due to a slight error in the transverse centre of gravity position. This is as a result of the internal video camera accidentally shifting position slightly just prior to the run.

5.2(b) Water levels in compartments

The initial water level in the starboard tank on the 2nd Deck (2Centre-S12) is higher when the KG value was higher, as the higher KG values result in greater initial heel angles, Figure 16. This probe is fully submerged upon reaching the equilibrium position for all values of KG.

For the lower KG value the model did not heel to port, and consequently the level of water during the run in the two compartments on the 2nd deck on the port side (2Aft-S11 and 2Centre S15) was significantly lower than for the other runs, as seen in Figures 17 and 18.

For both the lower KG values water did not reach the wave probe at the rear of the aft compartment on the starboard side on the 2nd deck (1Aft-S17).

The equilibrium heel angle and the maximum port heel angle (intermediate heel angle) are plotted as functions of KG in Figure 19. The run with the KG value of 163 mm had an initial equilibrium heel angle of 0.7º to starboard. Therefore, the results in Figure 18 for this run were adjusted by 0.7º to give the difference in heel angle from the initial condition. It is assumed that this will give a reasonable estimate of the heel angles that would have been obtained had the model been ballasted correctly.

As can be seen, both the equilibrium heel angle and the maximum angle to port were greater when the KG value was greater.

6. CONCLUDING COMMENTS

A series of experiments has been conducted in calm water on a 3.268 metre long model of a generic destroyer hull form to generate data to further validate the flooding module in a non-linear time domain ship motions code.

With the model initially stationary, a rapid damage event was generated, and the global motions measured, along with the water levels in some of the internal compartments, as functions of time.

Immediately after the damage occurred the model rolled to starboard (towards the damage). It then rolled to port (away from the damage) before eventually returning to starboard and settling at its equilibrium value. In all the tests conducted the equilibrium heel angle was less than that reached during the initial roll to starboard.

Five runs were conducted to investigate repeatability. The initial motion, and the initial rate of water level rise in the compartments were very similar in all these runs. However, the rate of roll motion and water levels in the compartments differed noticeably during the phase between the initial maximum roll angle to starboard, and the final equilibrium heel angle. The final equilibrium heel angle and final water levels in the compartments were similar in all these runs.

Tests were conducted at four different values of vertical centre of gravity. From these the value of the initial roll angle to starboard, the subsequent intermediate roll angle to port, and the final equilibrium heel angle, as functions of vertical centre of gravity, were determined. As expected, when the centre of gravity is higher these heel angles were higher.

7. ACKNOWLEDGEMENTS

The authors acknowledge the contributions from Mr Egbert Ypma and Dr Frans van Walree of MARIN.

8. REFERENCES

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2. Qualisys 2008, *Qualisys Track Manager - User Manual*, Version 2.1.4, November 2008, Qualisys AB.

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Length overall	3268	mm
Length between perpendiculars	2961	mm
Beam	412	mm
Draught	118	mm
Displacement	68.63	kg
LCG (forward of AP)	1418	mm
Roll radius of gyration	140	mm
Pitch radius of gyration	716	mm

Table 1 Model principal particulars

Run Number	**KG**	**Comments**
P1_8	163 mm	Effect of KG
P1_9	169 mm	Effect of KG
P1_12	173 mm	Repeatability
P1_14	173 mm	Repeatability
P1_15	173 mm	Repeatability
P1_16	173 mm	Repeatability
P1_20	176 mm	Effect of KG
P1_28	173 mm	Repeatability

Table 2 Test program

Figure 1 Profile (all dimensions in mm)

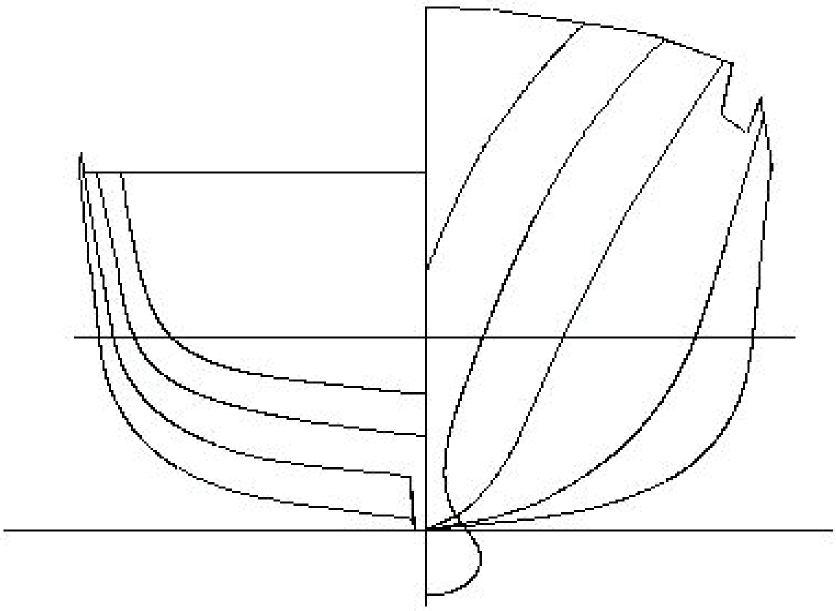

Figure 2 Body Plan

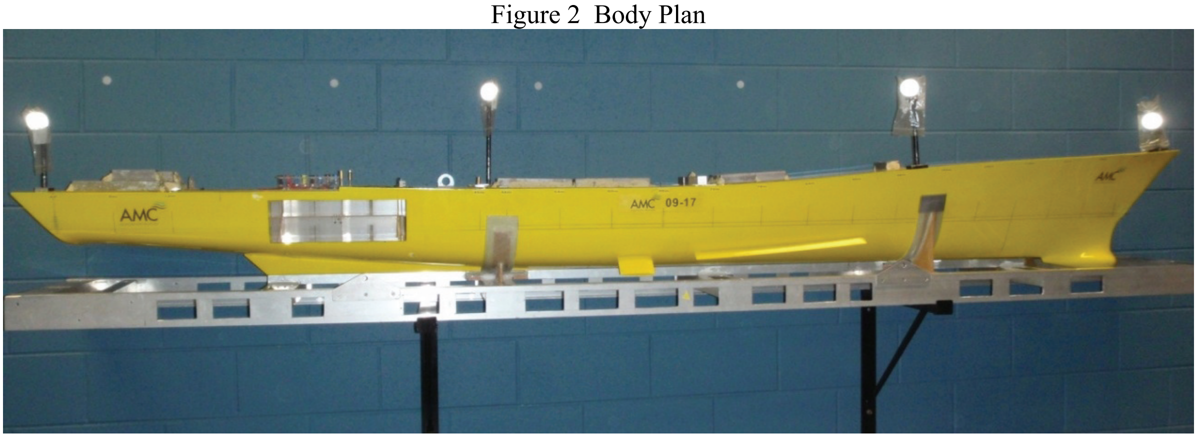

Figure 3 Photograph of model

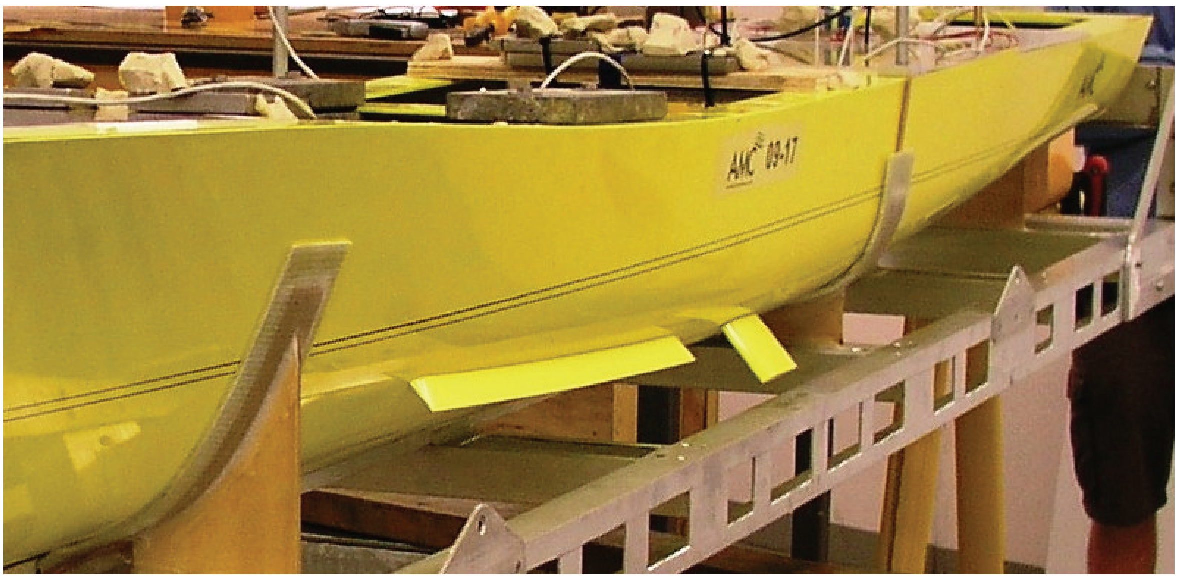

Figure 4 Bilge keel and fixed stabiliser fin

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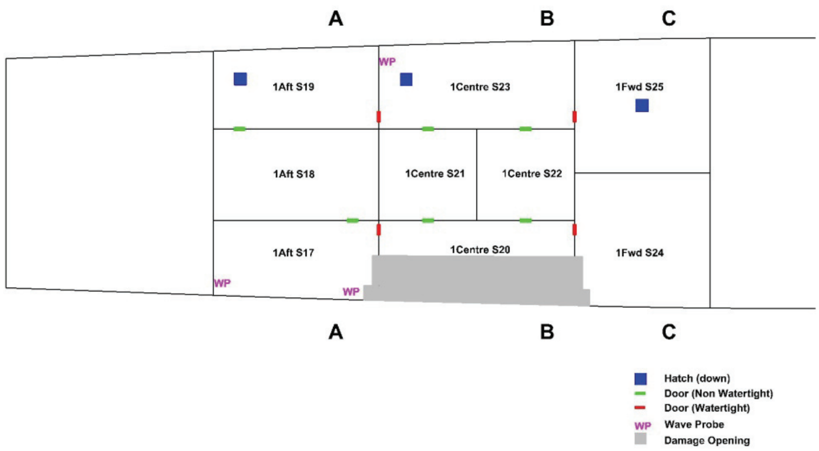

Figure 5a Plan of 1st Deck

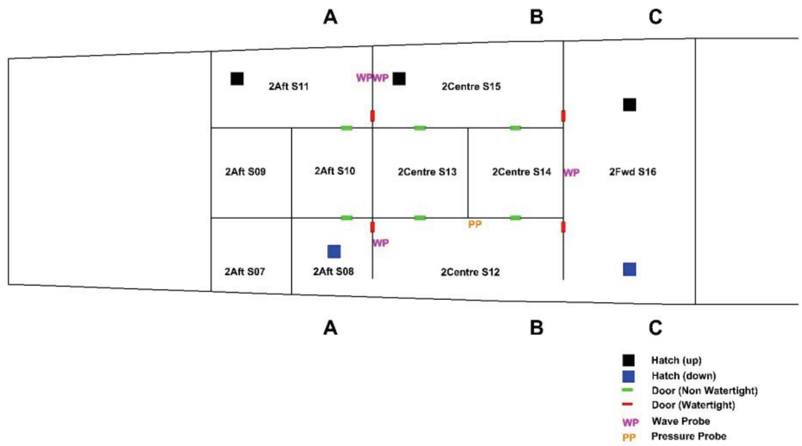

Figure 5b Plan of 2nd Deck

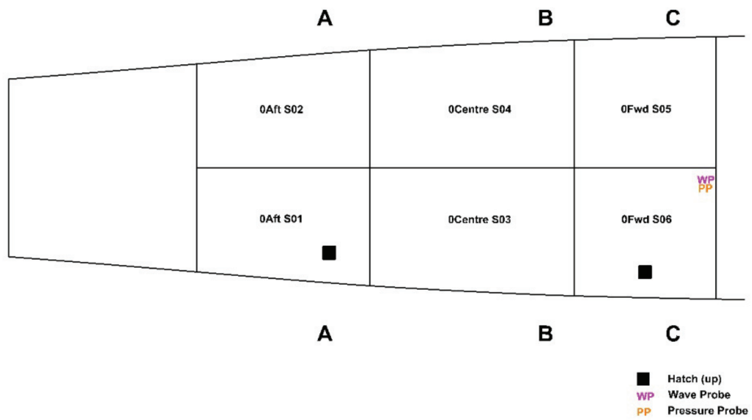

Figure 5c Plan of Tank Deck

Figure 6a Cross-section AA

Figure 6b Cross-section BB

Figure 6c Cross-section CC

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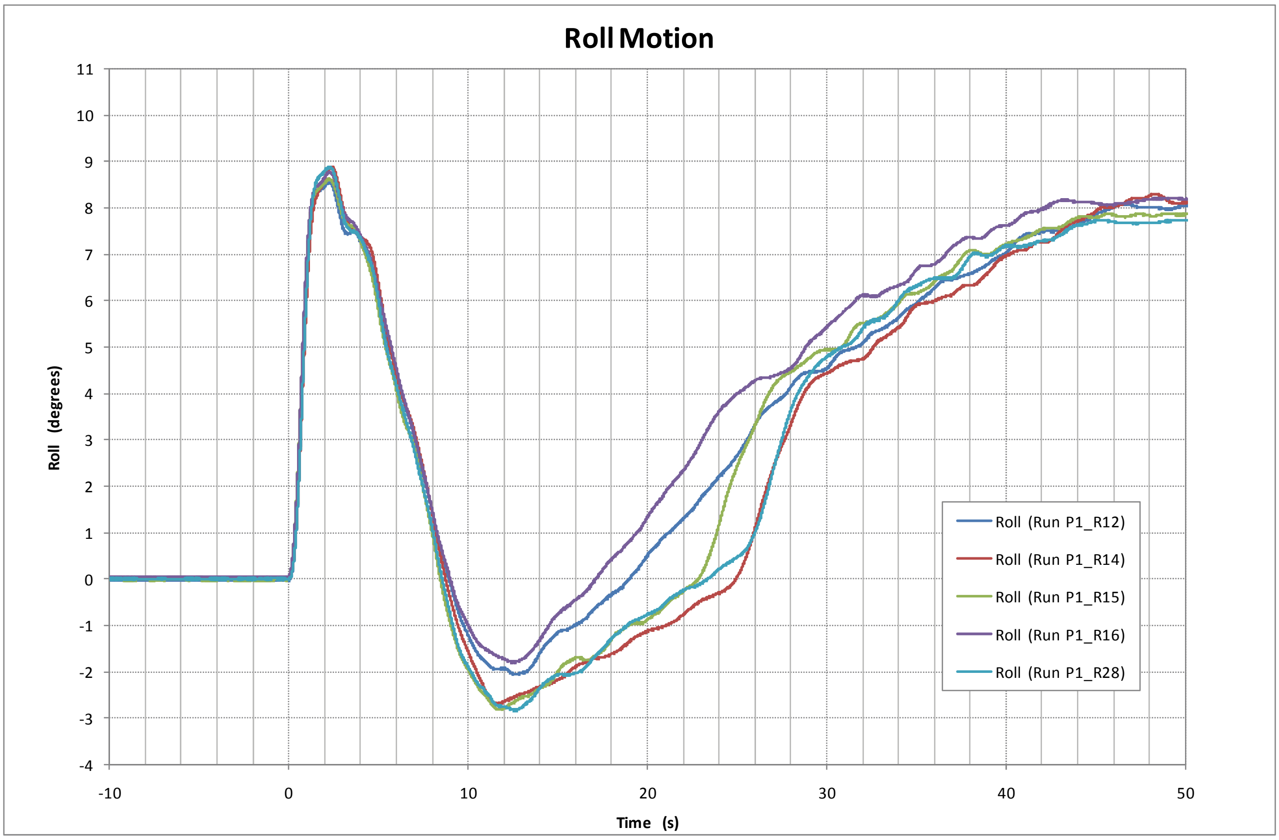

Figure 7 Roll as a function of time

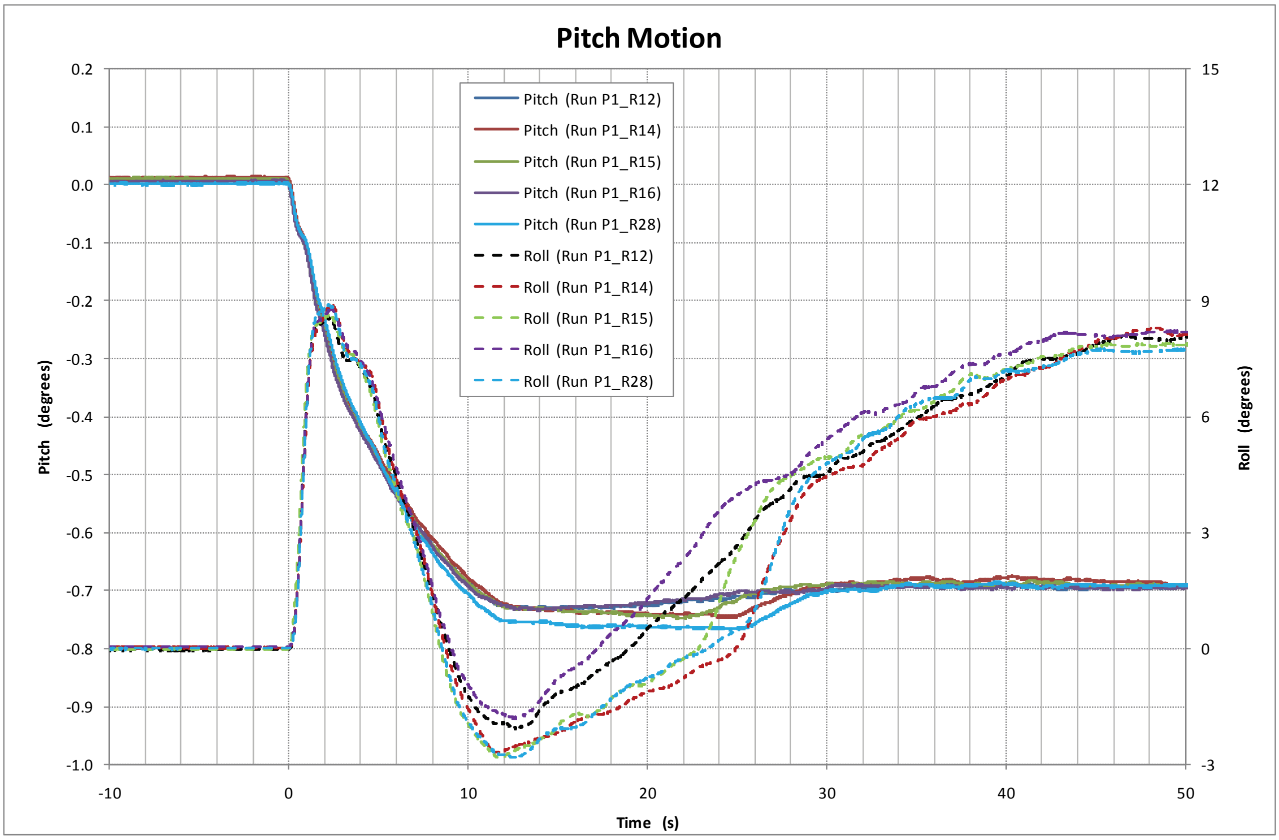

Figure 8 Pitch as a function of time

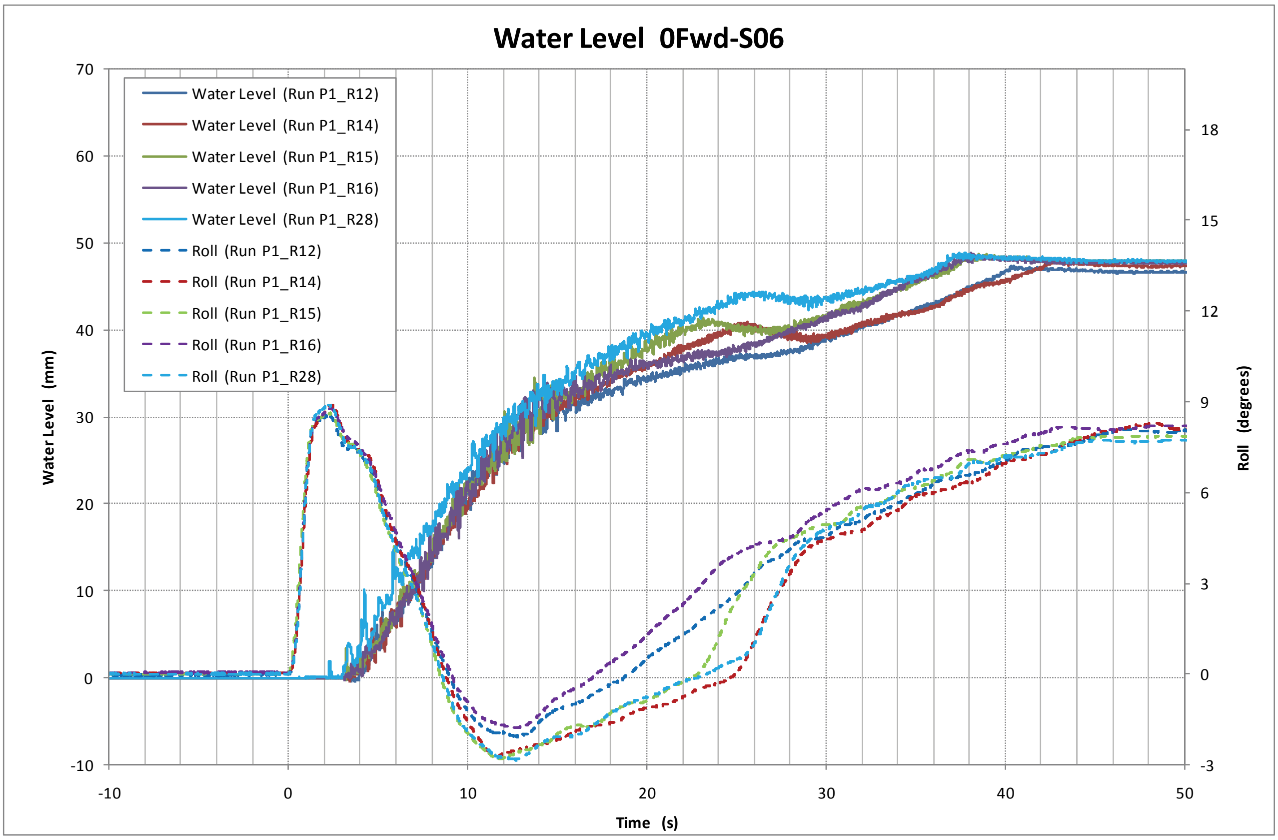

Figure 9 Water level at 0Fwd-S06 as a function of time

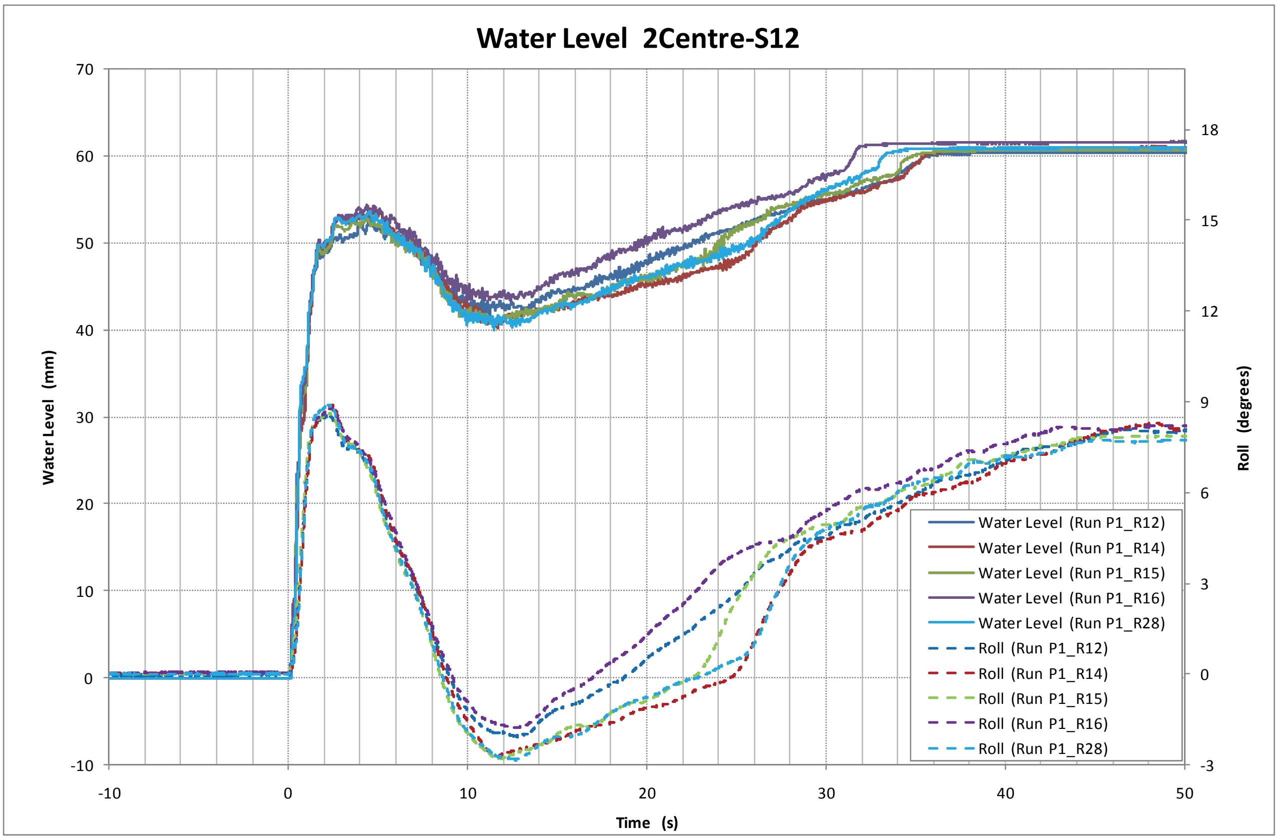

Figure 10 Water level at 2Centre-S12 as a function of time

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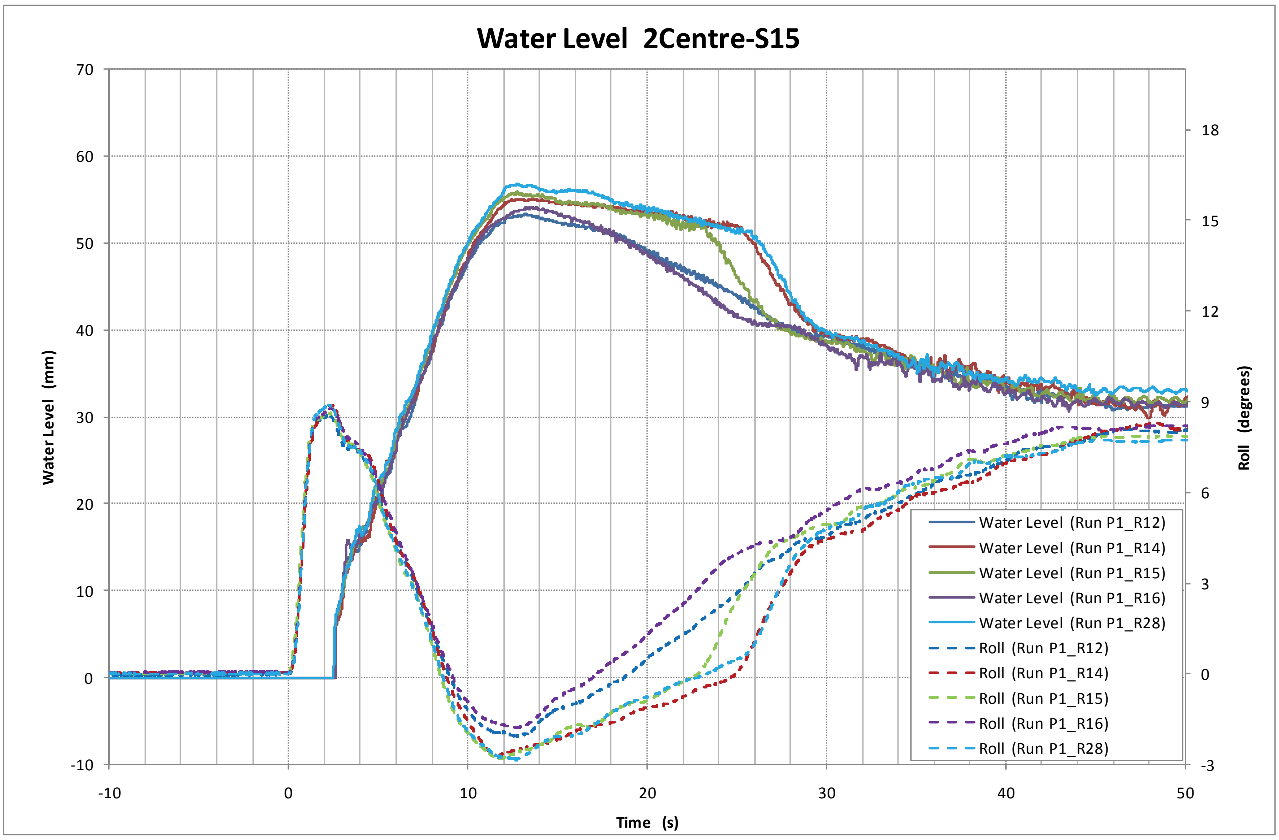

Figure 11 Water level at 2Centre-S15 as a function of time

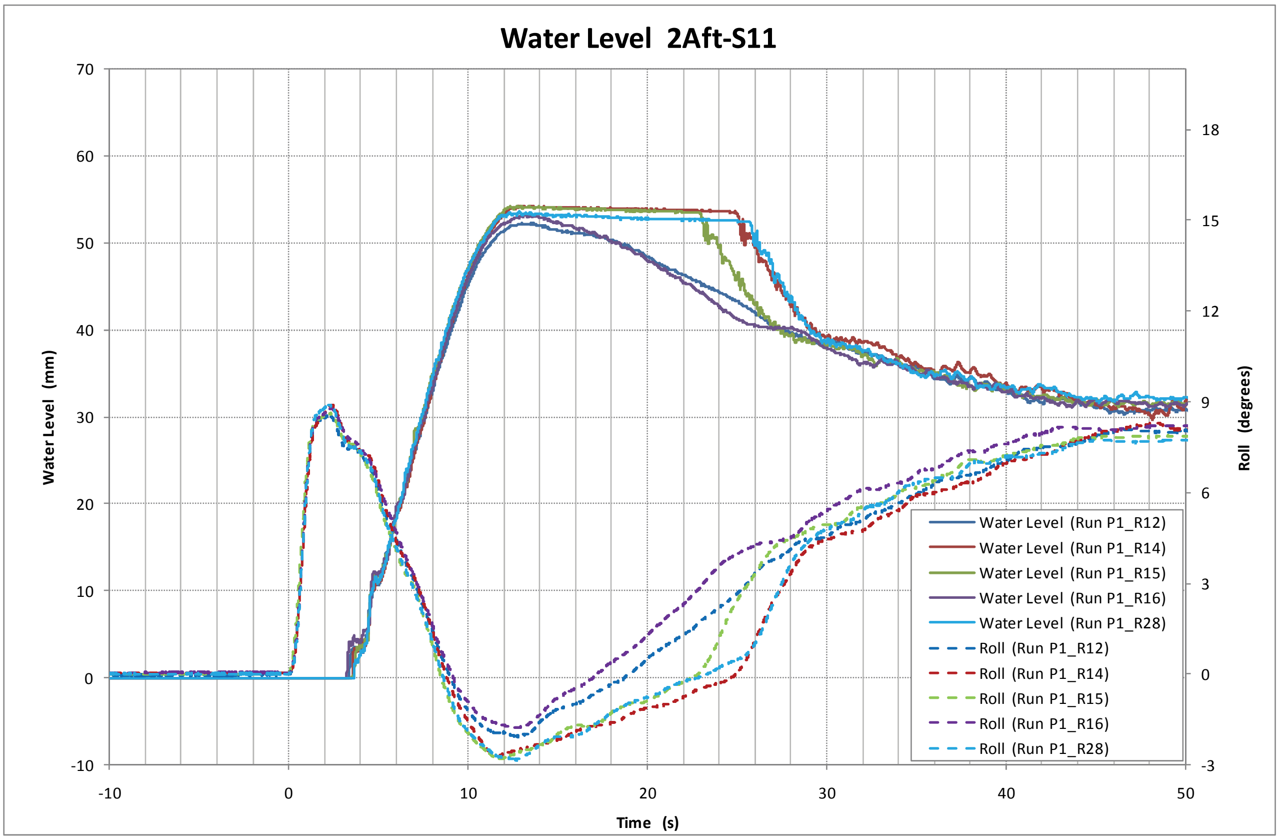

Figure 12 Water level at 2Aft-S11 as a function of time

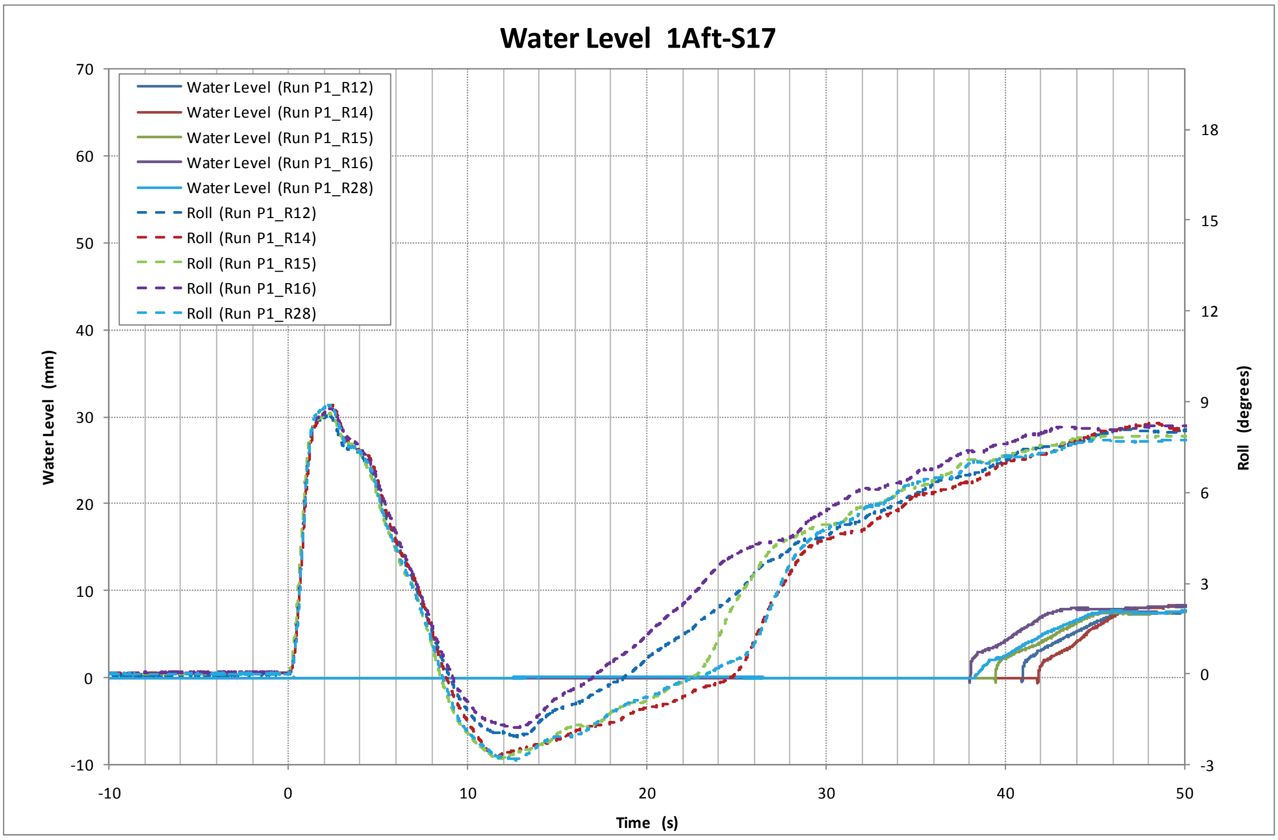

Figure 13 Water level at 1Aft-S17 as a function of time

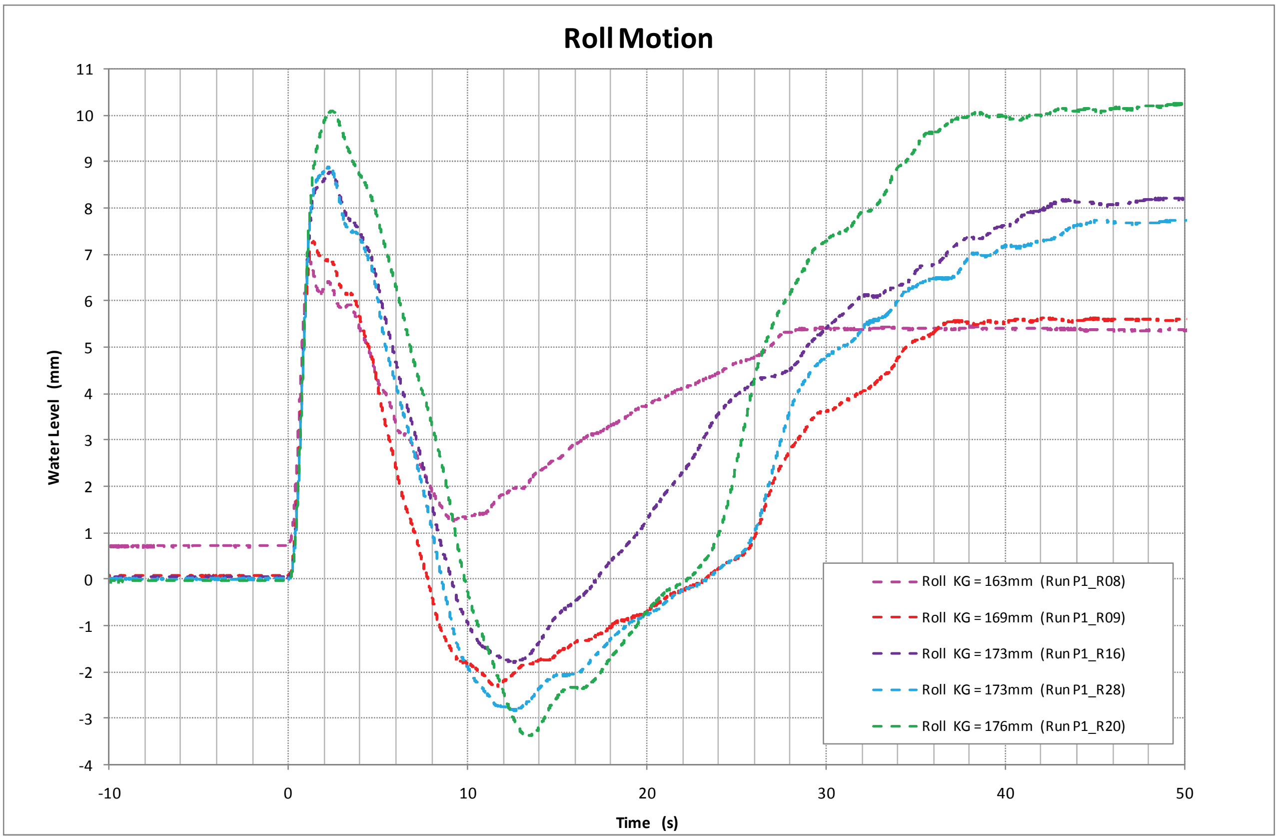

Figure 14 Roll as a function of time

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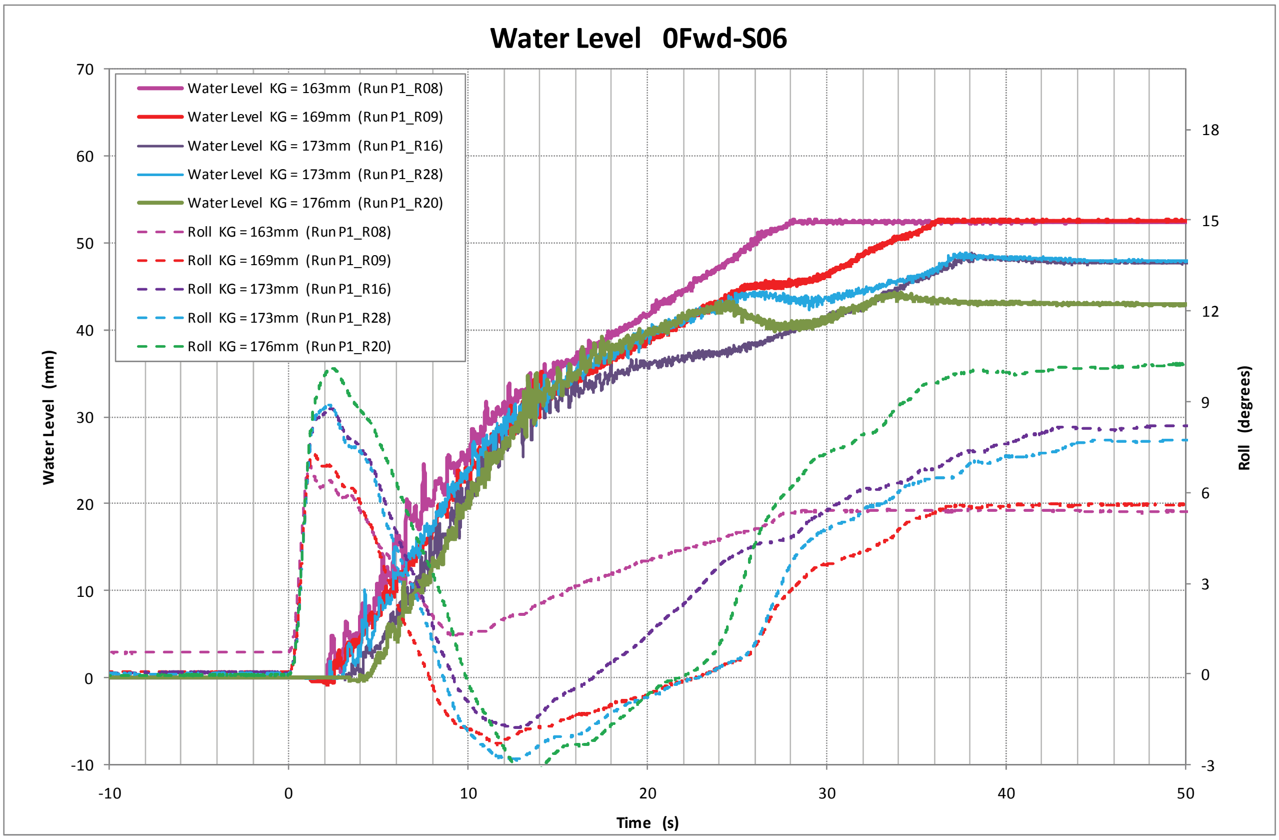

Figure 15 Water level at 0Fwd-S06 as a function of time (effect of varying KG)

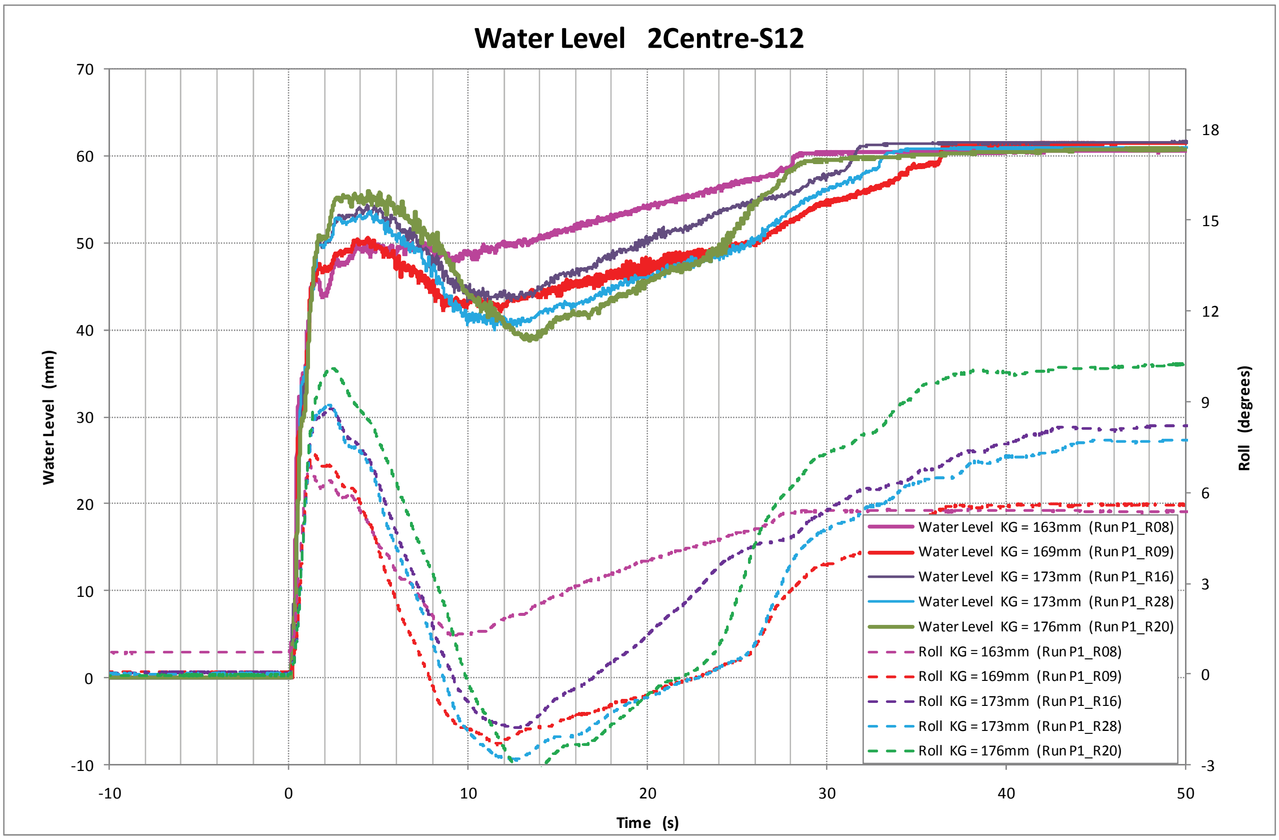

Figure 16 Water level at 2Centre-S12 as a function of time (effect of varying KG)

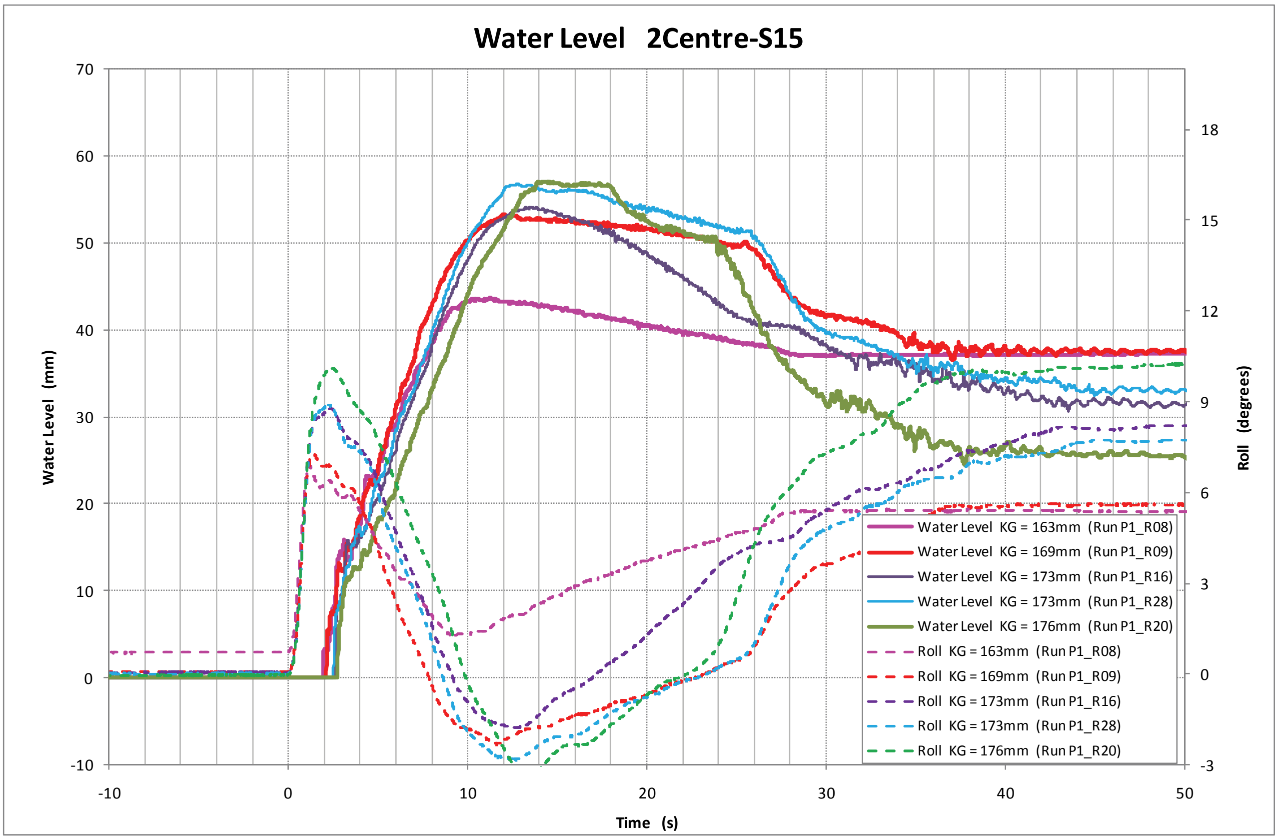

Figure 17 Water level at 2Centre-S15 as a function of time (effect of varying KG)

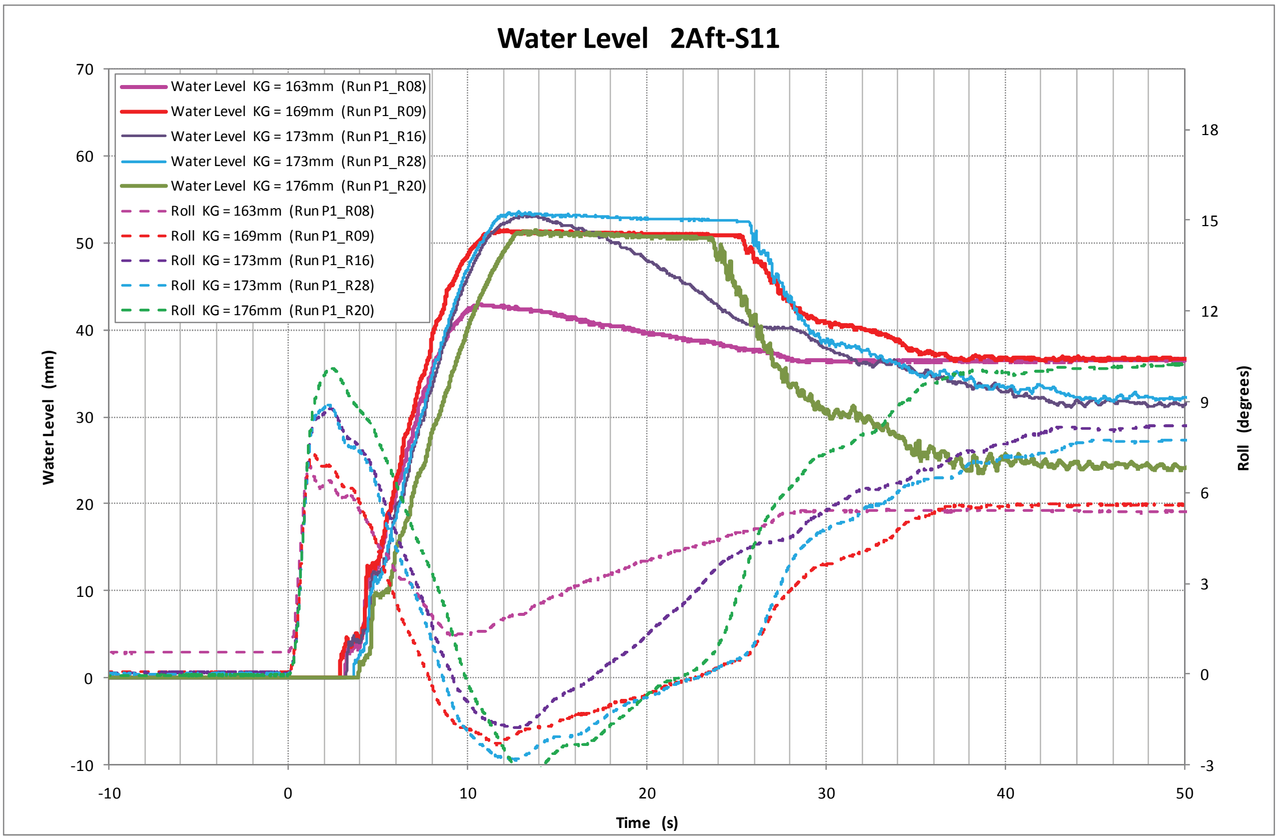

Figure 18 Water level at 2Aft-S11 as a function of time (effect of varying KG)

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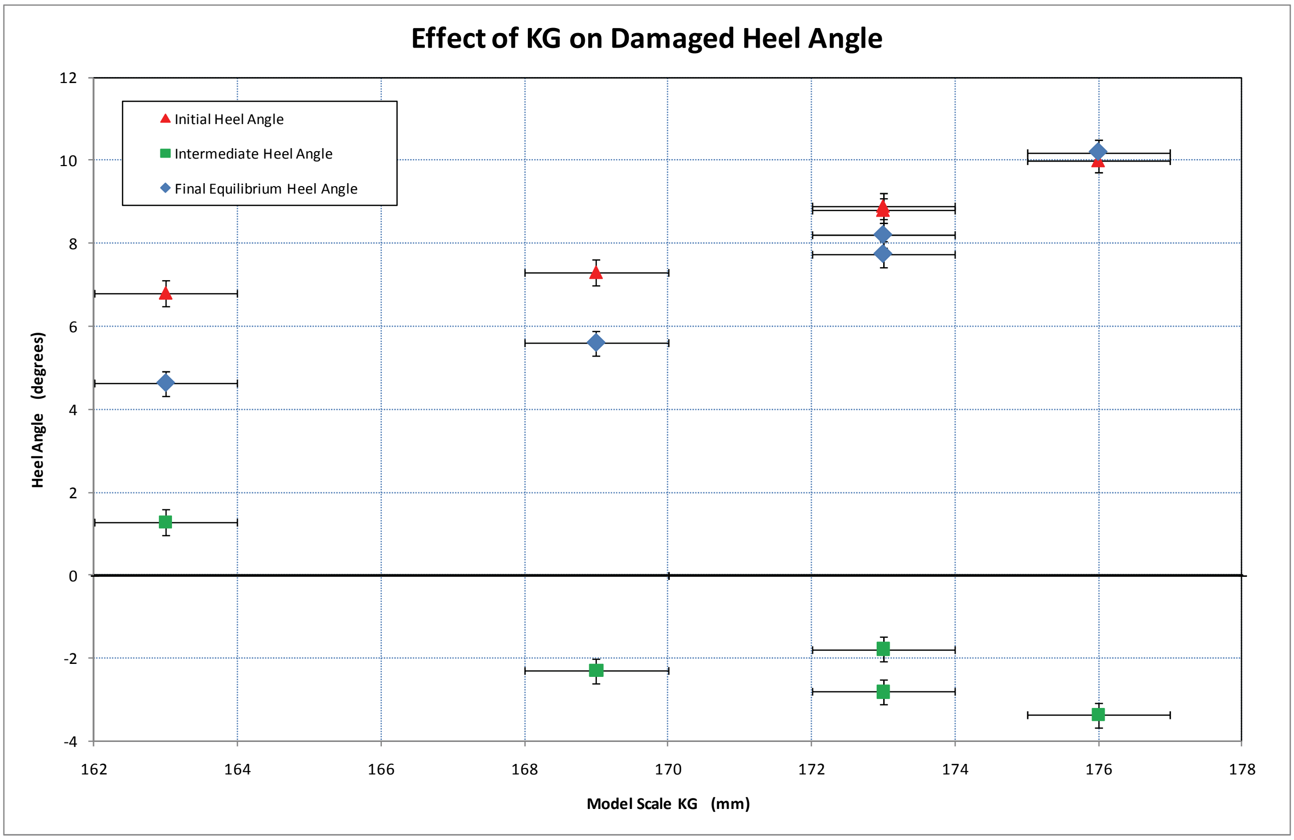

Figure 19 Effect of KG on damaged heel angles