

The Effect of Shallow Water on Roll Damping and Rolling Period

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## ABSTRACT

Significant effort has been made to quantify and predict roll damping of vessels in the past. Similarly, efforts have been made to provide effective methods for calculating the roll gyradius of vessels. Both the damping and the gyradius of a vessel are traditionally quantified through the use of a sally test. Experience with the *USS Midway* showed that shallow water has significant effect on the rolling period and thus the experimentally determined roll gyradius. To date, little effort has been directed to the problem of the effect of shallow water on roll damping and roll period except when trying to match model and full scale experimental data. No clear guidelines exist for the boundary between deep and shallow water or the amount of overprediction of roll period that is likely for a given water depth. In order to provide greater understanding of the effects of shallow water on roll period and roll damping, this thesis performed experiments in varying scale water depths for 5 models: 4 box barges and a model of the *USS Essex*.

The following conclusions were reached: As water depth to draft ratio,  $d/T$ , approaches 1 the roll period can increase as much as 14%. The boundary between deep and shallow water is a water depth somewhere between 4 and 7 times the vessel draft depending on the particulars of the vessel's hull form. Vessels with a larger beam to draft ratio will experience shallow water effects in relatively deeper water, that is to say the depth to draft ratio will be greater at the upper limit of deep water. Additionally, vessels with a higher beam to draft ratio will experience larger shallow water effects for a given depth to draft ratio. Finally, for vessels of very fine hull forms, the boundary between deep and shallow water will occur at relatively shallower depths, in other terms, the boundary will occur at a lower depth to draft ratio.

## Dedication

To my lovely wife Jane, may we always love and cherish one another as we do now.

## Acknowledgements

Many people deserve acknowledgement for their part in my completion of this thesis. First, my supervisor Craig Gelfenbaum deserves a large share of credit for putting me on a collision course with this topic. He initially had me work on an improved method of longitudinal weight distributions, which later influenced a better method of determining the roll gyradius of a ship. This later work also included attempts to validate the calculation from full scale data. This in turn led to reading about the troubles with the Midway and discovery of the interesting problem of roll period in shallow water. Thanks Craig for putting me on the path to this work and for all of your guidance over the years.

My parents also deserve a lion's share of credit for encouraging me to pursue a Masters degree and for always being there when work and class seemed too much at the same time, to tell me to pull it together and get it done because they knew I could.

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## 1.0 Motivation

In order to perform a seakeeping calculation for a ship, a number of inputs are required. After defining the hull form and providing the displacement and centers of gravity of the vessel, one of the major inputs to the seakeeping calculation is the ship's roll gyradius. The standard way to calculate roll gyradius is to sum the transverse moment of inertia for every item in the ship's weight database as if each item was a point mass. If the items in the weight database are small enough, the result can be very close to the true gyradius [1]. However, depending on the way information is stored in the weight database, the transference method may result in unrealistic errors. These difficulties can be overcome by using a distribution integration approach [2]. Because the roll gyradius is such an important parameter in the motions of a vessel and it is the result of a very large calculation, it is preferable to be able to quantify it based on experimental results. Unfortunately, a ship is far too large to perform a Lamboley test (a method of determining the mass moment of inertia of an object by making it the weight at the end of two differing length pendulums and comparing their periods of oscillation [3]); however, the ship can be sallied to determine the roll period and the roll gyradius can be calculated from the rolling period. The result of a pierside sally test can lead to serious overestimating of the gyradius of a ship due to the shallow water effect. Ricketts and Gale [3] discuss this with respect to the problems with the *USS Midway*. The *USS Midway* was a World War II era aircraft carrier that was approaching the end of its useful life. The vessel had longitudinal strength, stability and freeboard deficiencies due to the weight and KG growth over its lifetime. In order to address these problems and extend the ship's life by several years, the ship was blistered in 1986. Blistering is the adding of large protrusions to the underwater form of the vessel in order to give it greater stability. Unfortunately, rather than simply solve the existing problems, the blistering of *USS Midway* led to excessive intact stability and excessive roll motions, which interfered with aircraft operations. These poor motions combined with excessive deck wetness and other problems associated with the blistering led to the removal of the *USS Midway* from service within five years. The lack of understanding of the effects of shallow water on the rolling period of a vessel was a contributing factor to the failure of the *USS Midway's* blistering and the ultimate removal from service of this major warship for poor seakeeping. If the roll gyradius of the *USS Midway* had been properly estimated during the design phase of the blistering project, the design may have been different and the project may well have succeeded. If the shallow water impact on roll period was understood, the sally of the completed ship would have indicated that something was wrong before the vessel went to sea; instead, the sally test seemed to confirm the design estimates. One of the recommendations given in Ricketts and Gale's paper was as follows:

“An analytical method of predicting the effects of water width and depth restrictions on ship roll periods determined by sally experiments is needed. Criteria need to be established for minimum water width and depth needed for the sally results to closely approximate open-ocean values. Model sally experiments for several principal ship types varying water width and depth could be used to establish preliminary criteria in the short term and also to validate the ultimate analytical approach [3].”

To date, to the knowledge of the author, there have been no papers published addressing shallow water effects on period and damping. This thesis begins to explore the impacts of shallow water



by using box barges and a ship form model and compares these results to the limited historical data. Inglis and Price [4] gave limited data at a depth to draft ratio of 1.1 and Gawn [5] provided curves of extinction for models of the *HMS Nubian* and *HMS King George V* in both shallow and deep water. However, neither of these studies was seeking to generally quantify the effect of shallow water on roll period and roll damping.

## 1.1 The History of Roll Damping Studies / Literature Review

Early equations used to describe ship rolling, such as those by Wooley [6] and Rankine [7] neglected damping entirely. Froude notes that the authors of the early papers containing these equations did not neglect discussing damping (which he refers to as “the resistance offered by the medium in which the ship oscillates”) however, “it has hardly been regarded as of the great importance which in truth belongs to it” and, they nevertheless did not include it in their equations [8]. Froude goes on to explain the importance of damping to the problem of rolling:

For it is unquestionable that if the oscillations were performed independently of “resistance,” a ship of any ordinary form if by chance exposed to waves the period of which is the same or very nearly the same as her own, would inevitably be rolled over to a fatal angle in the transit of a few waves of ordinary steepness. [8]

Further, Froude points out that, “under the circumstances which produce maximum rolling in any given ship, it is to resistance alone that she owes her safety; and the truth of this assertion is in effect absolutely unshaken by the other defects of the theory [8].” Put in modern terms, without damping, any vessel encountering a wavetrain that would cause it to experience large amplitude rolling would certainly capsize.

In this same paper, Froude goes on to discuss what has become known as the sally test, exciting a vessel to roll by moving weight back and forth and then stopping this forcing and allowing the ship to freely roll in still water. The decay of the rolling thus created is used to quantify the rolling characteristics of the ship and the period of rolling in the sally test is taken as the ship’s natural period. The sally test is the basis of the experimental data in this thesis. Froude describes the sally test as follows:

It has been found quite easy in practice to give to very large ships, even those of high statical stability, oscillations of considerable range in still water, by running the crew from side to side, nicely timing the run to suit the motions of the ship. And it has been found equally easy to obtain results from which the resistance of the ship can be deduced, by stopping the men, the moment a sufficient oscillation has been thus established, and allowing it to be extinguished by resistance. The course of extinction has been made to record itself automatically on a travelling sheet of paper, in the shape of a series of quasi-harmonic curves, referred to the zero angle as abscissa, the spacing of which may be taken to represent time, or count of oscillations indifferently (for it is found that up to all ranges within the read of such experiment the oscillations are, as one would expect, practically isochronous), while an ordinate to the curve at any point measures the inclination of the ship at the corresponding moment of time or fractional part of an individual oscillation denoted by the divisions of the abscissa. Could such an experiment be performed in absolutely still water, it is obvious that a properly executed graphic integration performed on the data which this curve presents at any part, if the scale were sufficiently open, would show the

absolute force of resistance which was at the moment operating; at least if the ship's curve of stability were known. But practically in the course of all the experiments now referred to, it has been obvious that there was enough surface undulation to produce at least so much inexactness of result as is inconsistent with the nicety which this integration requires, and it has been necessary to infer the law of resistance somewhat more generally, by noting the loss of range which occurs from oscillation to oscillation – by comparing, in fact, what Newton calls the “descensus” and the “ascensus” for the successive swings [8].

The rolling history of a ship can be presented in a number of ways. One is the “Curve of Declining Angles”. In the Curve of Declining Angles, the number of oscillations is plotted along the horizontal axis and the absolute value of the angle to which the vessel rolled at that oscillation is plotted along the vertical axis. A curve is then faired through the points. An example of the Curve of Declining Angles is given in Figure 1. The other method of presenting the data begins to show the damping the vessel experiences. This is the Curve of Extinction. In the Curve of Extinction, the angle of roll is plotted along the horizontal axis and the “extinction” or change in rolling angle from one oscillation to the next is plotted along the vertical axis. Figure 2 shows a sample Curve of Extinction.

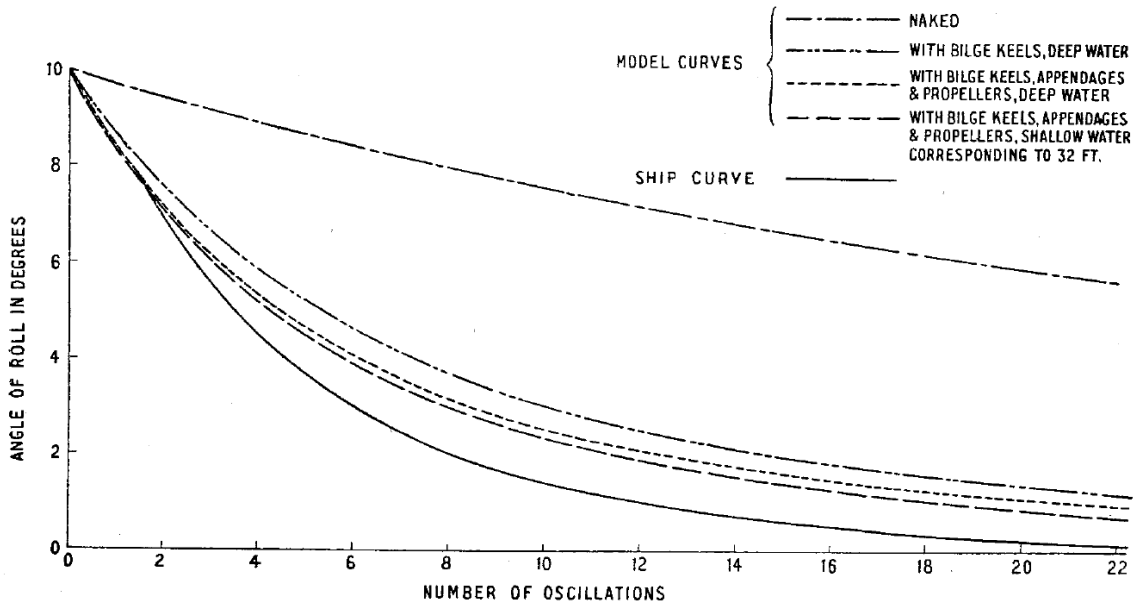


Figure 1: Curve of Declining Angles for *HMS Nubian* Figure 7 of [5]

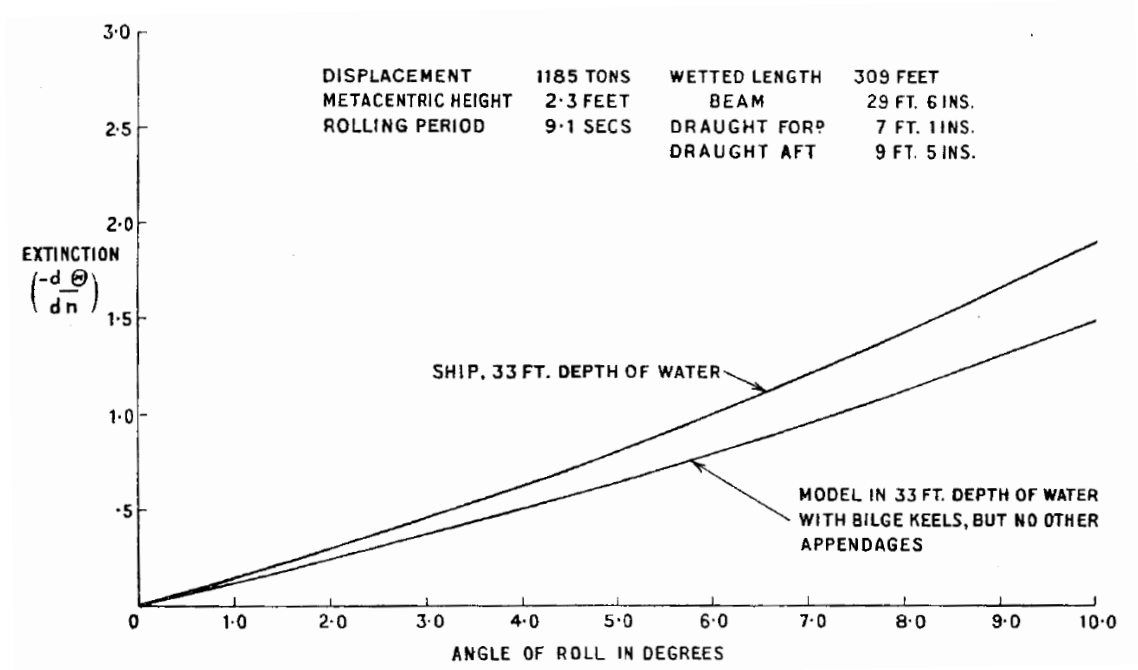


Figure 2 Curves of Extinction for *HMS Vivian* Figure 8 of [5]

Froude predicts that the form of the curve of extinction is

$$-\frac{d\theta}{dn} = a\theta + b\theta^2$$

In this equation  $d\theta/dn$  is the change in roll amplitude between half cycles or extinction,  $\theta$  is the roll angle and  $a$  and  $b$  are coefficients determined by fitting. Froude attributes the  $a$  term to damping due to wave formation and the  $b$  term to friction and bilge keel effect.

A later paper by Froude describes an apparatus for recording the roll motion of a ship which enabled capturing of the data needed to analyze the sally test [9].

Froude’s method of recording sally data and using declining angle curves and curves of extinction to quantify rolling behavior became widely adopted. In an 1874 paper [10], Froude argues that M. Bertin’s assertion in a Naval Science paper earlier that year that the proper form of the curve of extinction was:

$$-\frac{d\theta}{dn} = b\theta^2$$

Froude did this by comparing the actual curves of extinction of four ships, three British and one French, with those calculated according to the equations proposed by M. Bertin and himself. In all cases Froude’s formulation showed vastly superior agreement than Bertin’s. It appears that this settled the issue as the next mention of Froude’s equation seems to be in William White’s 1895 paper [11]. White used Froude’s methodology to quantify the effect of bilge keels on the

damping of *HMS Revenge*. Three years later, across the Atlantic in the United States, similar results were obtained on experiments with the *USS Oregon* [12].

Adams found that curves of declining angles for models of *HMS Sultan* and *HMS Inconstant*, two of the ships whose data was published in Froude's 1874 Naval Science article, did not show good agreement with those of the actual vessels [13]. He found a potential cause of this disagreement in the damping was provided by the significant amount of rigging these vessels possessed as it moved through the air. Adams also explored the effect of loose weights on the declining angle curves. His plots indicate for the models he was using that the impact is not significant in the early stages of the sally test (angles over 10 degrees) but when the test run time is extended, the impact can be as much as 1 degree (circa 60 rolls with his model).

Gawn chronicles efforts to obtain a satisfactory match between sally tests of models and the ships they represent [5] [5]. His first figure, taken from Plate XIX of the Report of the Committee on Inflexible 1878, shows good agreement between the Curves of Declining Angles for the ship and her model; however, although Gawn reports that Froude used a model that was "ballasted to give the correct centre of gravity to scale and the correct radius of gyration to represent the dynamical conditions of the ship" the displacement and other data of the model and the ship at the time of the experiments are not known. As a practical matter, it is unlikely that Froude really knew the gyradius of the *HMS Inflexible* in the test condition with high fidelity because this requires a tremendously detailed weight calculation and a detailed deadweight survey, exceeding the level of detail that was feasible before computers [14]. Additionally, even highly detailed weight calculations are often found to disagree with the results of an inclining experiment and dunnage survey. While this disagreement is small and unimportant in terms of ship displacement, the effect on the accuracy and uncertainty of a radius of gyration calculation is magnified. Gawn states that the purpose of his trials on a ship recently completed had, "the immediate object of comparing her rolling qualities in still water with those of the model which had been tested some time previously. Although on the face of it the trial had an academic purpose, it had a more practical objective, namely to check whether the improvements in anti-rolling effect of different arrangements of keel obtained with models of ships of current building programs would be borne out on the full scale [5] [5]." Gawn's principle results are shown for the *HMS Nubian*, a Tribal Class destroyer of the 1935 Programme. Figure 6 of his paper compares the Curves of Extinction of the ship and her model, with the model systematically altered from naked to fully appended and then additionally tested in a basin of scale depth. This appears to be the first time investigations were made into the effect of water depth on damping. Gawn found that the damping was 8 per cent greater at 7 ½ degrees in the scaled shallow water. However, the damping of the ship and the model still did not agree. In the same paper, Gawn went on to compare the Curves of Extinction of two more ships, *HMS Vivian*, a World War One era destroyer, and *HMS King George V*, a battleship completed in 1912. In both cases there is disagreement between the ship and the model damping. Gawn does present model data of *HMS King George V* complete with bilge keels and docking keels in deep water and in water of 42 scale feet. While Gawn does not present a similar plot for *HMS Vivian*, in the text he does state that, "there did not appear to be any measurable influence on damping due to the shallowness of the water."

Gawn [5] [5] theorized that the discrepancy between ship and model scale damping is primarily caused by some unquantified scale effect on the bilge keel damping. In the discussion of this paper, G. S. Baker suggests that an uneven bottom profile in the full scale experiments or differences in the arrangement of the mooring lines may have had some influence on the discrepancies as well.

Robb reviewed and summarized the prior investigations into the resistance of rolling motion [15]. He concluded, based on Gawn's data from the *HMS Nubian* experiments, that "it is not possible to determine the curve of declining angles, or the curve of extinction, for a ship from experiments on a model." Robb also pointed out that both the  $a$  and  $b$  coefficients increased with the fitting of bilge keels in the *HMS Revenge* and *HMS Nubian* studies; he used these results to conclude that Froude's conclusions on the action of bilge keels were incomplete because Froude's theory would only have the  $b$  coefficient change. Robb also published  $a$  and  $b$  coefficients and decrement plots for models of "a later 'Royal Sovereign' class [15]" in the original condition and with two different bulges, with and without bilge keels. A review of Burt's definitive history of British Battleships [16] shows this class was the Royal Sovereign Class of the 1913 estimates. These decrement plots, reproduced here as Figure 3, show that for angles above about 12 degrees, the decremental equations are only approximate (above this the curves tend to flatten out). The corresponding midship sections are shown in Figure 4.

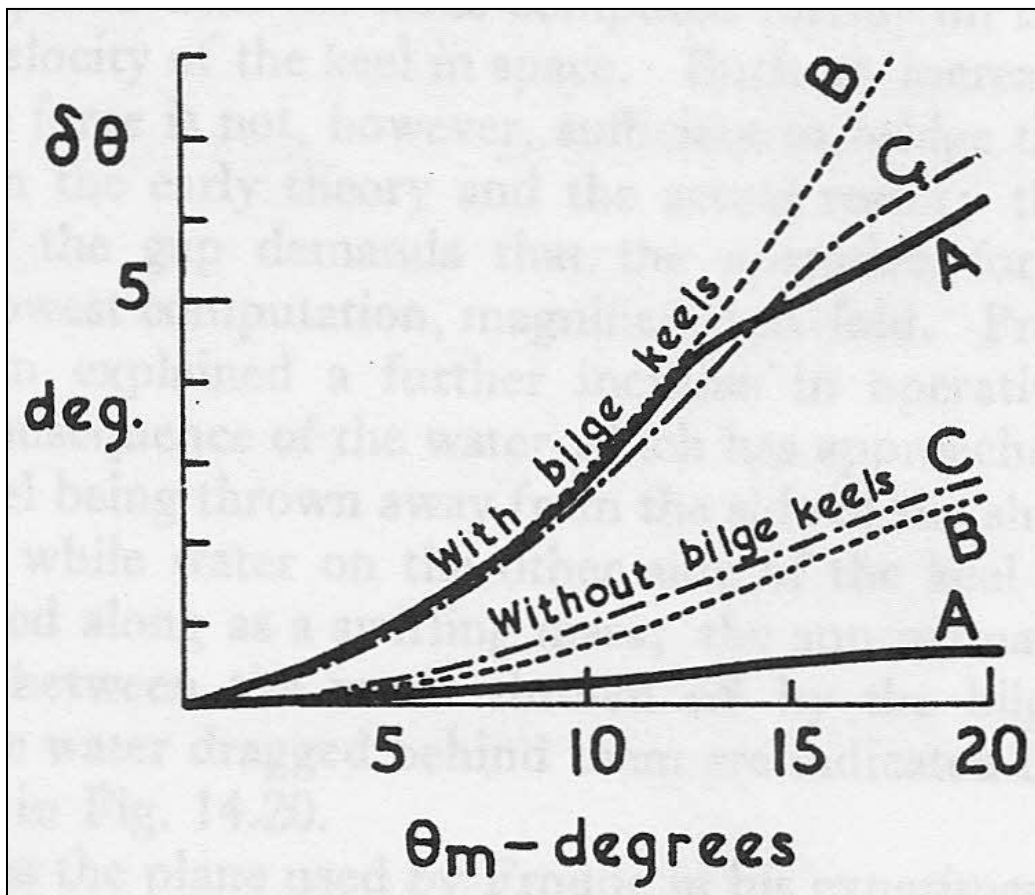


Figure 3: Roll Decrement Curves for the Royal Sovereign Class Figure 14.18 of [15] curve labels correspond to models with the midship sections in Figure 4

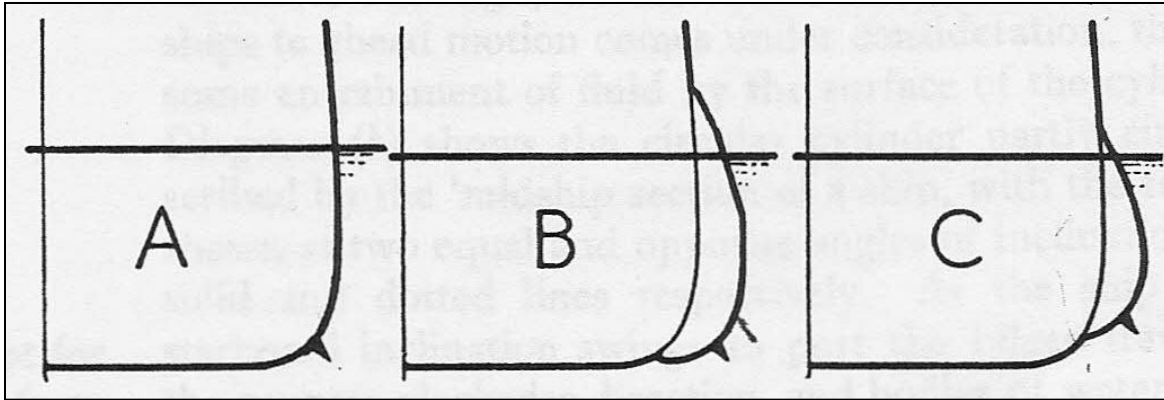


Figure 4: Midship Sections for Figure 3, Figure 14.17 of [15]

This data is different from that published from previous experiments on other ships. Robb concludes this section of his book with a discussion of the merits of calculating the radii of gyration from records of rolling periods. He states, “It is possible, but is scarcely practicable, to calculate the moment of inertia of the mass of a ship; an approach to accuracy of calculation would demand very great labour.” After calculating the radii of gyration,  $K$ , of the *HMS Revenge* based on data with and without bilge keels, Robb points out that the effect of the bilge keels on the length of the roll period affects the prediction of  $K$ . This leads to his conclusion that “the values of  $K$  determined from periods of roll are over-assessed; more so when bilge keels are fitted”. Robb additionally points out that the radii of gyration for a ship based on rolling period is actually the radii of gyration of the vessel and the entrained water. Robb’s arguments lead to the conclusion that because the rolling period as unaffected by resistance to rolling and the mass of the entrained water are unknown, determining the radius of gyration of a ship in air from rolling records with certainty is impossible. It should be noted however, that all of the problems with this approach that Robb highlights lead to an over-prediction of the radius of gyration. This means that the value calculated from the rolling record could be useful as an upper bound for comparison with a calculation.

Dalzell reviewed various theoretical formulations of the damping function as well as attempts to linearize them [17]. He notes that for practical applications, the theoretical models do not match reality, “In fact, what are considered realistic estimates of [roll damping coefficients] are almost totally empirical. In the vast majority of studies where some distinction is made between the ‘linear’ and ‘quadratic’ components of roll damping, the numerical results are obtained by analysis of ship or model sallying experiments. The data-reduction approach has been basically the same since the time of Froude.” Dalzell goes on to examine the relative merits of a mixed quadratic plus linear fit (as per Froude) and a mixed cubic plus linear fit. The mixed cubic plus linear fit has the benefit of being inherently an odd equation which is desirable for using the damping in the equation of motion. Dalzell compared the fits based on published data of sally tests results including those published by Froude and Gawn. Dalzell’s conclusion was that the cubic plus linear fit could be considered an “equivalent approach”.

Inglis and Price explored the effect of shallow water on ship motions [4]. They note previous work by Kim showed that the “effects of shallow water become perceptible when the water depth is approximately four times the ship’s draught ( $d/T = 4$ ) and for  $d/T < 2$  the shallow water effects can be significant.” Inglis and Price used a three dimensional method to calculate the

motions of a ship in six degrees of freedom. They specifically calculated the motions of a fine form ship traveling at Froude numbers of zero and 0.15 in regular sinusoidal waves in three water depths,  $d/T = 1.1, 2$  and  $\infty$ . They found that damping increased with decreasing water depth. The natural roll period increased from 12.7 seconds in infinitely deep water to 13.7 seconds in water of  $d/T = 1.1$  [4].

Himeno reviewed the state of the art in roll damping prediction [18]. Himeno did not use Froude's formulation, but summarized work of several others that predicted the roll damping based on predicting the damping due to each component (friction, eddy, lift, wave and bilge keel) and linearly combining them. While the two "simple" methods that Himeno opens his review with are informed by specific ship types (Series 60 and Containerships in one, and distinct coefficients for Container, Cargo, Ore Carriers and Tankers in the other) the detailed method, based on determining each component of damping individually, has general applicability. The correlations between model tests and Himeno's method are for vessels with block coefficients of 0.7-0.8 [18].

Following the troubles with the *USS Midway*, Ricketts and Gale highlighted the impact that shallow water had had on the ship's roll period during a sally test [19]. They went on to make a number of recommendations, two of which have direct bearing on the problem of a ship's roll motion:

- "An analytical method of predicting the effects of water width and depth restrictions on ship roll periods determined by sally experiments is needed. Criteria need to be established for minimum water width and depth needed for the sally results to closely approximate open-ocean values. Model sally experiments for several principal ship types varying water width and depth could be used to establish preliminary criteria in the short term and also to validate the ultimate analytical approach. [19]
- Procedures are needed to calculate a ship's radii of gyration (mass moments of inertia) about the three principal axes during the design process and to routinely update these estimates as the ship weight estimate is developed and refined. Reliable data in this regard are needed in order to correctly assess ship dynamic behavior both analytically and in the model tank. This is certainly achievable given modern computer technology. [19]"

The rolling period as discussed in the first recommendation is essentially governed by the increase in roll damping due to blockage effects. No currently published works have addressed this phenomenon beyond the limited data provided by Gawn [5] [5] and Ricketts and Gale [19]. The second recommendation was addressed by Cimino and Redmond [1] and later by Hansch [14]. Building upon this historical motivation, the following paragraphs provide a brief summary of the state of modern roll damping research.

Brook used sally data from Gawn [5] [5] to evaluate theoretical methods of predicting roll damping [20]. Particularly, Brook evaluated methods by Ikeda, Schmitke and BMT. Brook found that "no single theoretical method consistently gives accurate roll damping coefficients for all vessel types and conditions." He found the prediction of damping at large angles to be particularly troublesome. Of the three methods, examined, Brook found the BMT method to be the most reliable. The discussion following the paper highlights the value of the historic full scale sally data as replicating such an experiment would have been prohibitively expensive.

Ikeda et al published a paper comparing model experiments to prediction methods previously proposed by Ikeda in [21]. Ikeda found that his prediction method worked well when the rolling amplitude was less than four degrees but over-predicted the damping coefficient when the roll amplitude was greater than four degrees.

Chakrabarti revisited the approach of Himeno, and expressed the roll damping coefficient as the sum of five components: hull skin friction, hull eddy shedding damping, free surface wave damping, lift force damping and bilge keel damping [22]. Chakrabarti illustrated the methods he presented with data for a container ship and a derrick barge.

Kawahara et al presented a simplified method of predicting roll damping along the lines of Ikeda's method [23]. This simplified method requires only several parameters of the ship rather than detailed data on cross sections of the vessel. Comparisons of the damping predictions yielded by the simplified method and Ikeda's original method are shown for two vessels and are favorable.

Jang et al presented a new method for determining the nonlinear damping moment [24]. They discussed methods of dealing with the stability problems in solving the integral equation involved and then compared the results of their method to the parametric approximations. Finally they compared the results of both method's predictions of the free roll decay with actual model test data for a fishing vessel.

Fernandes and Oliveira discuss a different approach to obtaining roll damping from decay tests. They point out that especially for hull forms such as those used in VLCCs, with significant flat of bottom and sharp bilges, the roll damping at high amplitudes is primarily a function of the large vortex shed at the bilge attaching to the bottom [25]. They point out that this damping mechanism differs from the mechanisms at lower roll amplitudes. Because the damping is dominated by different mechanisms in two different regions, Fernandes and Oliveira propose a bi-linear approach to the damping model where a linear damping coefficient is calculated for both the large and small amplitude sections. They propose connecting these regions with a hyperbolic tangent function through the transition region. At small angles of roll, Fernandes and Oliveira found the methods of Froude and Faltinsen to have similar performance to their bi-linear method, but those methods break down at large angles [25]. Interestingly, while this is a similar finding to Robb [15], the damping presented on the battleships falls off at high angles while those presented by Fernandes and Oliveira show the damping increasing.

Bassler et al built on the idea of a piecewise damping model from Fernandes and Olivera [25] to model damping fluctuations brought on by changes in damping regime such as bilge keel emergence [26], specifically, the emergence of the bilge keel reduced roll damping. The model used in the experiments supporting this work, the ONR Topside Series hull forms, is of a much lower block coefficient than the VLCC models in the experiments of [25]. The differences in hull form, and presumably the angle at which the bilge keels emerge, may well explain how one set of experiments shows the damping increasing rapidly at large angles and the other set shows it decreasing at large angles.



## 2.0 Theoretical Basis for Roll Damping and Period Dependence on Water Depth

According to Kent [27], G.S. Baker found that there are three damping forces created by a rolling ship: Skin Friction, Wavemaking and Viscous/Eddy making. Baker found that for three studied vessels the wavemaking portion of total damping varied between 7.5 and 20% and the Viscous/Eddy making portion of the damping varied between 60 and 84%. The influence of depth on each of these damping forces can be inferred as follows: There is no reason for skin friction to vary with depth, thus it can be discarded. Wavemaking and Viscous/Eddy making damping should change with water depth as the waves generated, and the flow field around the hull, are both impacted by the presence of the bottom.

Waves have a tendency to get slightly shorter and then significantly taller as they transition from deep water to shallow water. Thus it is reasonable to expect that the wavemaking damping may change. The wave height produced by the rolling ship and the changes to the wave height due to shallow water can be estimated by using an equation to predict the initial wave amplitude and then applying the traditional calculations to determine the effect of changing water depth on wave amplitude. Korvin-Kroukovsky [28] reports the following equation for the amplitude of the waves produced by a rolling ship as postulated by Ursell:

$$\zeta = 0.63k^2\varphi(b + d)(b + 1.05d)|b - 1.26d|$$

Where  $\varphi$  is the roll amplitude in radians,  $b$  is the half beam and  $d$  is the draft of the vessel.

Per Hudson [29], the change in wave height from deep to shallow water can be computed from:

$$H = H_0 \sqrt{\frac{C_{g_0}}{C_g}}$$

Where  $C_{g_0}$  is the deepwater group velocity and  $H_0$  is the deepwater wave height.

The group velocity  $C_g$  can be computed from:

$$C_g = \frac{C}{2} \left[ 1 + \frac{2kh}{\sinh 2kh} \right]$$

Where  $C$  is the wave celerity,  $h$  is the water depth and  $k$  is the wave number.

The celerity,  $C$ , is computed from:

$$C = \frac{gT}{2\pi} \tanh kh$$

Where  $T$  is the wave period and  $g$  is the acceleration due to gravity.

In order to illustrate the effect of change of water depth on a rolling vessel, Table 1 was computed for a model with a beam of 2.47 inches and a draft of 0.56 inches rolling 7.5 degrees.

**Table 1: Theoretical Effect of Water Depth on Wave Height for Waves Generated from a Rolling Model**

water depth (inches)	C (inches per second)	Cg (inches per second)	Wave Height, H (inches)
20	37.113	18.562	0.022
12	37.026	18.811	0.022
10	36.843	19.181	0.022
8	36.286	19.979	0.022
6	34.631	21.352	0.021
4	29.987	22.217	0.021
2	18.869	17.148	0.023
1	10.139	9.882	0.031
0.6	6.183	6.126	0.039

As the wave energy is proportional to the square of the wave amplitude, an increase in the size of the waves generated by the vessel rolling requires an increase in the amount of energy pulled from the rolling vessel. By definition removing energy from an oscillating system is damping.

Viscous/Eddy making drag is also affected by shallow water. In shallow water the shed vortices do not have room to form as they do in deep water. Newton's first law leads to the conclusion that the nature of the shed vortices in deep water is that that takes the least amount of energy from the rolling of the ship, thus it must be concluded that any change in boundary conditions which changes the nature of flow field will cause greater energy to be drawn from the rolling vessel, increasing the Viscous/Eddy making damping. Moving the bottom of the water into the flow field created by the ship's rolling ie the ship being in shallow water provides such a change. This hand waving argument can be illustrated by looking at the flow field around a rolling vessel in deep water and seeing how far it extends below the vessel's draft. Bassler et al [26] provided PIV measurements of a flow field of a rolling model. Their figure has been reproduced here as Figure 5. It can be seen in that if the water depth in this case is anything less than 400 mm the flow field around the model due to rolling will be altered by the presence of the bottom.

ANNEX A

LARGE AMPLITUDE ROLL EXPERIMENTAL RESULTS (BASSLER, ET AL., 2010A)

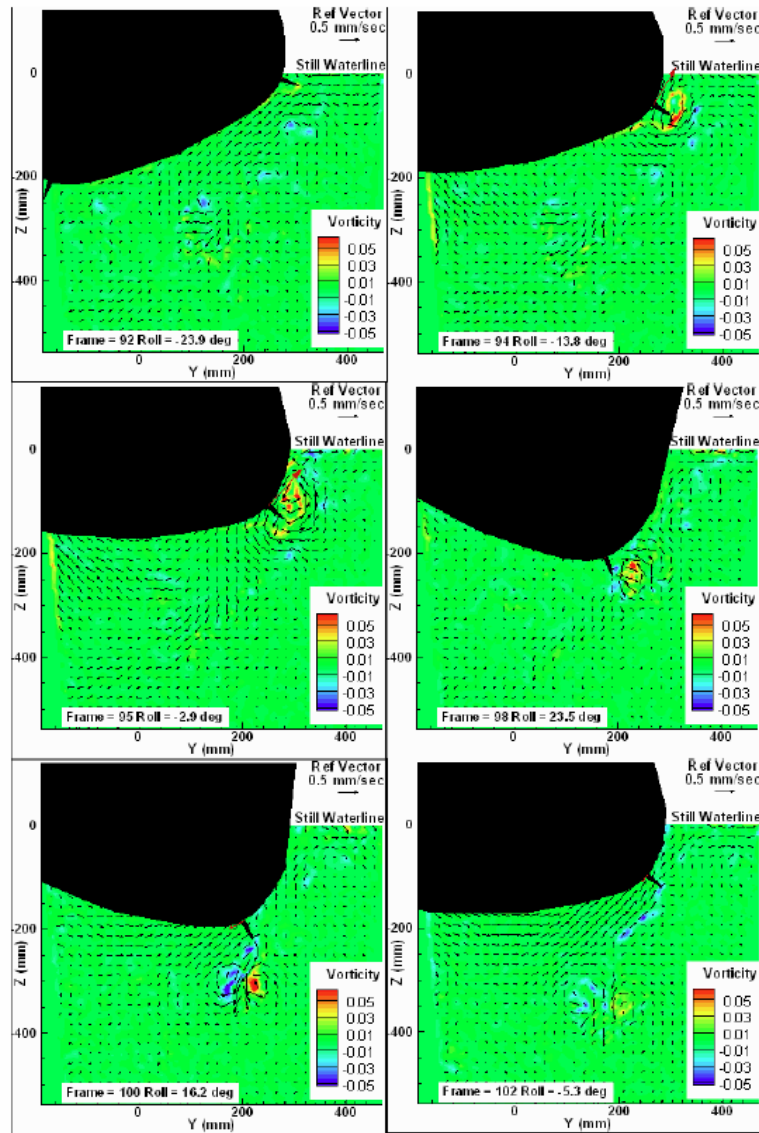


Figure 8: PIV measurements for  $\phi=25$  deg,  $\omega=2.5$  rad/s for DTMB Model #5699-1, with bilge keel force measurements shown (red vector). Single roll cycle shown (left to right, top to bottom), beginning after bilge keel re-entry (top left), near peak of the roll cycle when the bilge keel is fully submerged (middle right), and then transitioning to bilge keel emergence (bottom right).

Figure 5: PIV Measurements of the Flow Field of a Rolling Model Figure 8 of [26]

### 3.0 Experimental Setup and Methodology

In order to gain understanding of the magnitude of the effect of shallow water on roll period and damping as well as to quantify the limits of shallow water, 5 models were sallied in various water depths and the rolling motion was recorded. For each water depth and model combination

no less than 10 experiments were run. After each change in water depth, the basin was allowed to sit for 20 minutes to allow for any eddies or currents in the water due to the filling from a hose to damp out. In the smaller basin, hole-punchings were added to the water as a visual indicator to confirm that the water had no motion before testing was resumed. The larger basin was allowed to sit in excess of an hour between water level changes and sat overnight after initial filling before experiments.

### 3.1 The Models

Five models were used in these experiments. Three of them were box barges made of lexan glued together with pure silicone. The fourth model was built from the hull portions of a 1:350 scale model kit of the *USS Essex* made by Trumpeter. This model is fully appended with rudder, shafts, brackets and propellers. Table 2 gives the principal characteristics of each model. The naming convention is as follows: the 1 model is the baseline model, the 1.5 model has a planform that is 1.5 times the dimensions of the 1 model, the 1.5 T model is the same physical model as the 1.5 model ballasted with sand to achieve a greater draft, the long model has a longer L/B than the 1 model and the Essex model speaks for itself. Figure 6 and Figure 7 show one of the Box Barge Models and the Essex Model respectively.

**Table 2: Model Particulars**

Model	Length (L)	Beam (B)	Depth (F)	Draft (T)	Weight
	inches	inches	inches	inches	lbs
1	18.00	2.47	2.56	0.56	0.90
Long	20.00	2.47	2.50	0.53	0.95
1.5	27.00	3.75	3.91	0.51	1.875
1.5 T	27.00	3.75	3.91	1.65	6.03125
Essex	28.00	3.13	1.97	0.75	1.06



**Figure 6: Lexan Box Barge "1" Model**



**Figure 7: Close-Up on USS Essex Model Showing Appendages**

### **32 Instrumentation**

The time history of roll for each sally test was recorded using an iPod Touch and the Small Craft Motion Program (SCraMP) [30]. This program records the ship's attitude in roll, pitch and yaw at nominally 50 hertz. In order to improve the quality of the data to allow for analyzing damping, a modified version of SCraMP was used for several of the experiments. This version

allowed for recording at nominally 104 hertz. The accuracy of roll measurements from an iPod using SCraMP was compared with more traditional instrumentation at the United States Naval Academy Basin [31]. Additional analysis of the accuracy of SCraMP results is available in [32] and [33]. Overall the iPod was found to deliver results within 3% of the roll amplitude of traditional roll recording devices. At 104 hertz, the uncertainty of the time any individual peak appears is 0.009615 seconds. Thus, the uncertainty of the true period should be 0.019231 seconds.

### 3.3 The Basins

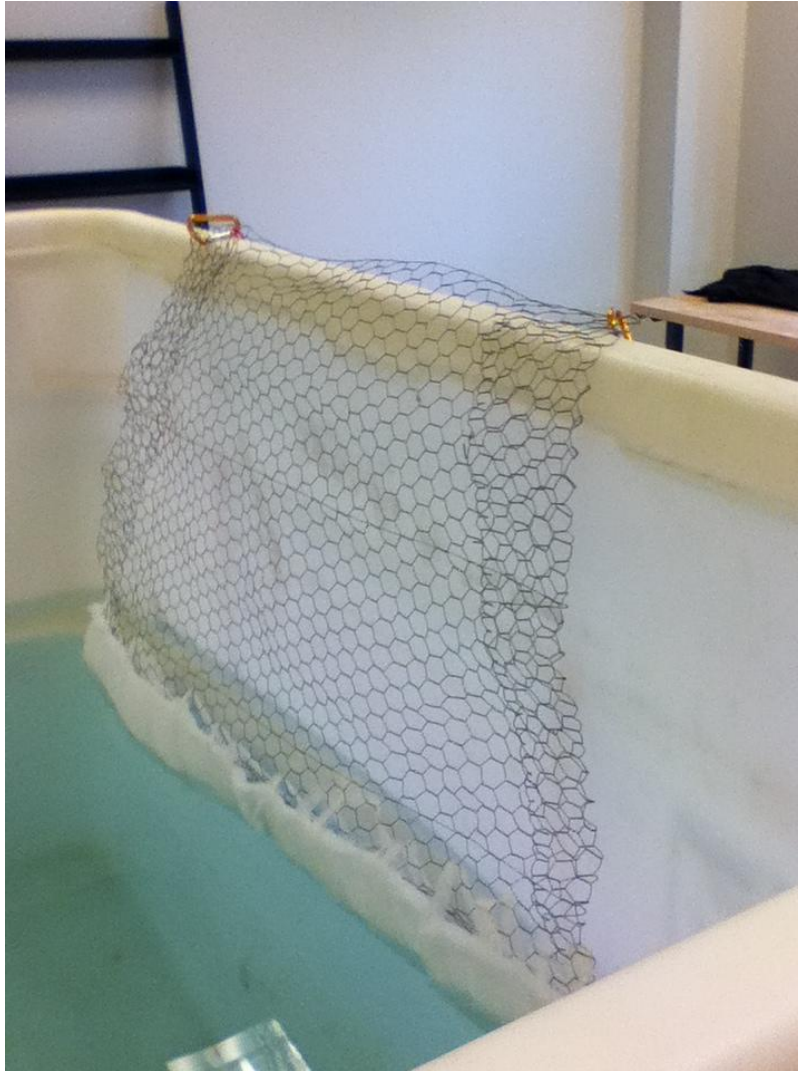
Two different model basins were used to perform these experiments. For water depths up to 16” a “My Sunshine 120” x 70” by 22” Deluxe Family Inflatable Swimming Pool” was utilized. The inside dimensions of this pool were 4’ x 8’ with rounded corners. For experiments at water depths greater than 16”, a 1325 gallon containment tank built by Den Hartog Industries was used. A technical drawing of this tank provided by the vendor is provided in Appendix A [34]. The surface area of this tank was 76-9/16” square at the water depths used for experiments. The deep water basin is located in a temperature controlled laboratory while the shallow water basin was set up in a garage that is not temperature controlled.

Each basin was outfitted with “beaches” made from strips of batting material secured to a framework of chicken wire with tulle netting material. These beaches were effective in reducing and almost eliminating wave reflection. Initial trials in the inflatable pool had indicated that without beaches this wave reflection would be a problem even in a basin whose sides were ~4’ from either side of the vessel. With the beaches fitted, wave reflection was not a problem even during tests with the model oriented so that the basin was less than 2 feet from either side of the model. The basins and beaches are shown in Figure 8 and Figure 9. The basins were filled with tap water from municipal water supply.



**Figure 8: The Shallow Water Basin Outfitted with a "Beach"**





**Figure 9: The Deep Water Basin Outfitted with a “Beach”**

### **3.4 Experimental Methodology**

In order to obtain sally test results, each model was manually deflected to roughly 20 degrees and released. The model was allowed to roll freely until the rolling appeared to have stopped; this generally took between 10 and 20 seconds. The model was then re-sallied until at least 10 runs had been completed for a given model and water depth combination. The data file was then transferred to the computer and quickly checked to verify that data had been collected. Then the experiments moved on to the next model or the next water depth. In the interests of efficiency, each model was sallied at each water depth. This means that all models were not sallied at all depth / draft ratios.

### **3.5 Data Processing Methodology**

In order to provide consistent analysis, the data was run through a custom MATLAB .m file which is included as Appendix B. The program automatically determines the length of “Good” data, finds the  $a$  and  $b$  damping constants for Froude’s equation and determines the rolling period of the model. In [8] Froude recommends fitting splines through the positive and negative peaks



in order to determine a true zero amplitude. This is important because the zero that is initially recorded is arbitrary and may not reflect the vessel in its “at rest” attitude. The  $a$  and  $b$  coefficients for Froude’s equation were found both using and not using this correction. The correlation coefficients for the coefficients found using Froude’s recommended correction were significantly higher than those determined without it. Figure 10 shows a comparison of the curves of extinction for the 1 Model at a water depth of 1.875 inches with and without Froude zeroing. The correlation coefficient in this case is 0.974 with Froude zeroing and a paltry 0.6012 without it. When the roll amplitude is too small, the signal to noise ratio for extinction becomes too low. Data in low signal to noise ratio regimes is neglected in the fitting of curves of extinction. The increase in signal to noise ratio can be seen in Figure 10.

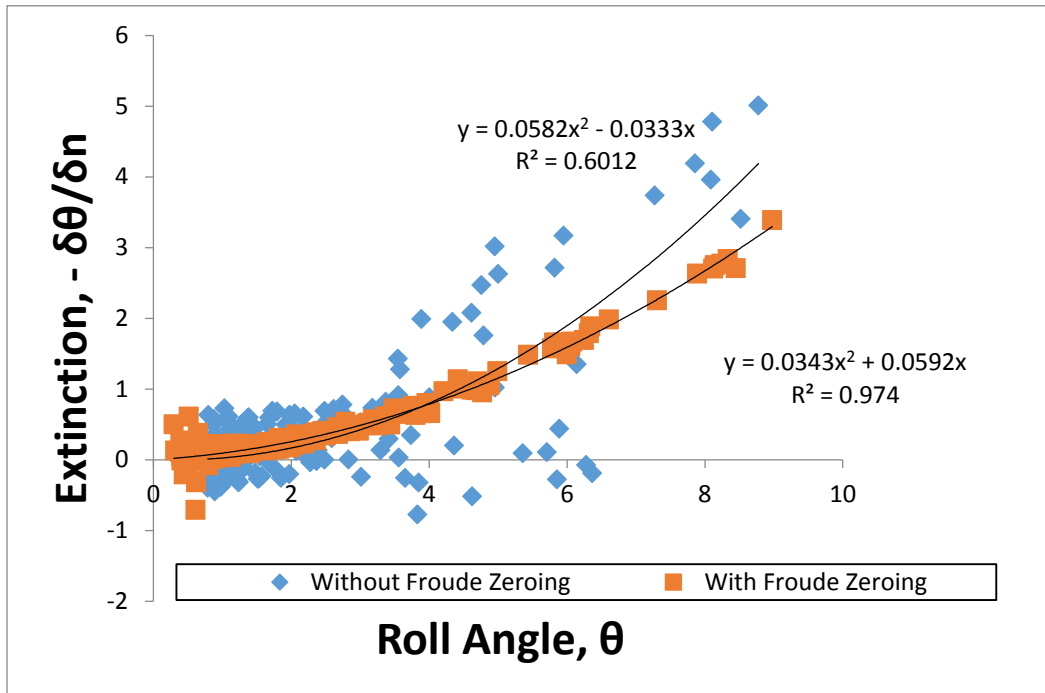


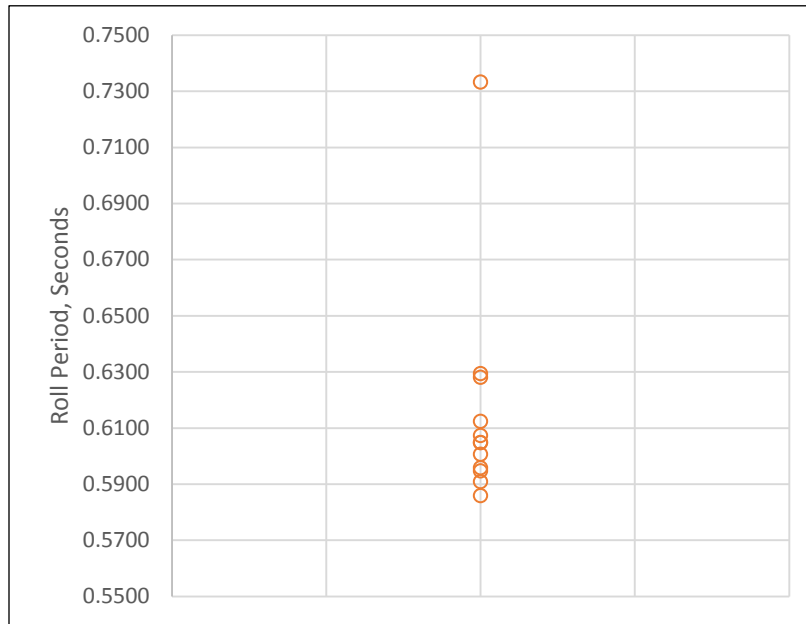
Figure 10: Curves of Extinction With (orange squares) and Without (blue diamonds) Froude Zeroing

There are two criteria that signal the end of “Good” data.

1. If the absolute value of the rolling amplitude increases between successive peaks.
2. If the half rolling period changes by more than 15% for any rolls after the 3<sup>rd</sup> cycle.

Using these criteria ensures that even though the length of each data sample may be different, all samples are trimmed based on the same principals.

The MATLAB .m file finds the rolling period of the vessel both by taking a Fast Fourier Transform, FFT, of the data as well as by subtracting the time between successive maxima and minima. Once the roll period was calculated for each of the experiments, the roll period for that model / water depth was determined by taking the average of the periods after excluding outliers using engineering judgment. As an example, Figure 11 shows the results for the 1 Model peak to peak periods. In this case the 0.7333 second result was considered an outlier and removed from the data set to be averaged. The FFT period results are reported as the standard deviation for each dataset was generally lower than the peak to peak period results.



**Figure 11: Roll Period Plot for Detecting Outliers**

### 3.5.1 Pre-processing Raw Data

Occasionally, there are slight issues with the raw data, which cause the program to be unable to determine the location of the peak. The program looks for changes in the direction of the instantaneous angle from always increasing to always decreasing or vice versa to determine the location of a peak. Essentially there are two potential problems that would cause the program to incorrectly locate a peak. First, two successive data points could have the same amplitude. In that case, the program fails to detect a change in the sign of the derivative between successive points and does not detect a peak. The second potential data issue occurs when there are additional small amplitude high-frequency effects in the rolling data. These generally do not change the nature of the data when the rolling velocity is high (in the middle of a roll) but can cause multiple peaks in the vicinity of the true peak. In this case, the data is slightly tweaked to allow the program to find the true peak in the data. This is done by adjusting the amplitude of the points that are not in keeping with the oscillatory nature of the data by the smallest amount possible in order to allow the program to find the location of the true peak. In all cases the original data is also retained if needed to support future studies.

### 3.5.2 Potential Sources of Error

The most likely source of error in still water rolling tests is the presence of waves or currents. The beaches mitigated the effects of reflected waves until the rolling amplitude was very small. Currents were more difficult to prevent and detect. Potential sources of currents include effects of previous experiments, disturbance of the basin walls and residual currents from filling or draining the basin. While efforts were made to prevent and visualize flow in the basins, it is very difficult to detect and control.

It is also difficult to ensure that the model reacts to the release in pure rolling. As noted in several of the papers discussed in the literature review, forward motion increases roll damping. The models were carefully released for each run with the goal of obtaining pure rolling; however, the models did move about during some experiments. Density variations between tests is another source of uncertainty; however, all tap water is of a fairly consistent temperature year round and the variation in density for tap water at 60° and 80° F is only 0.24% [35]. While the temperature records for the experiments were misplaced, it is believed that the water temperature for all experiments was between 68° and 78° F. Thus the variation in water density is likely to be a small fraction of one percent.

## 4.0 Results and Discussion

### 4.1 Rolling Period

Rolling period results are presented in non-dimensional fashion in Figure 12. Figure 13 through Figure 17 split these results out for each individual model. These period results do not fully match expectations. If shallow water effects on waves are taken as an example, one would assume that the effect on roll period would asymptotically approach zero with increasing  $d/T$ . While that is generally the case, the 1.5 T model seems to show no effect of shallow water on rolling period and the 1 Model and Long Model both have data points that appear to clearly be deep water with period greater by about 7% than other data points both shallow and deep. Additionally, the Long Model and the 1 Model have shallow water values where the period is reduced rather than lengthened when compared to the clearly deep water points of  $d/T > 70$ .

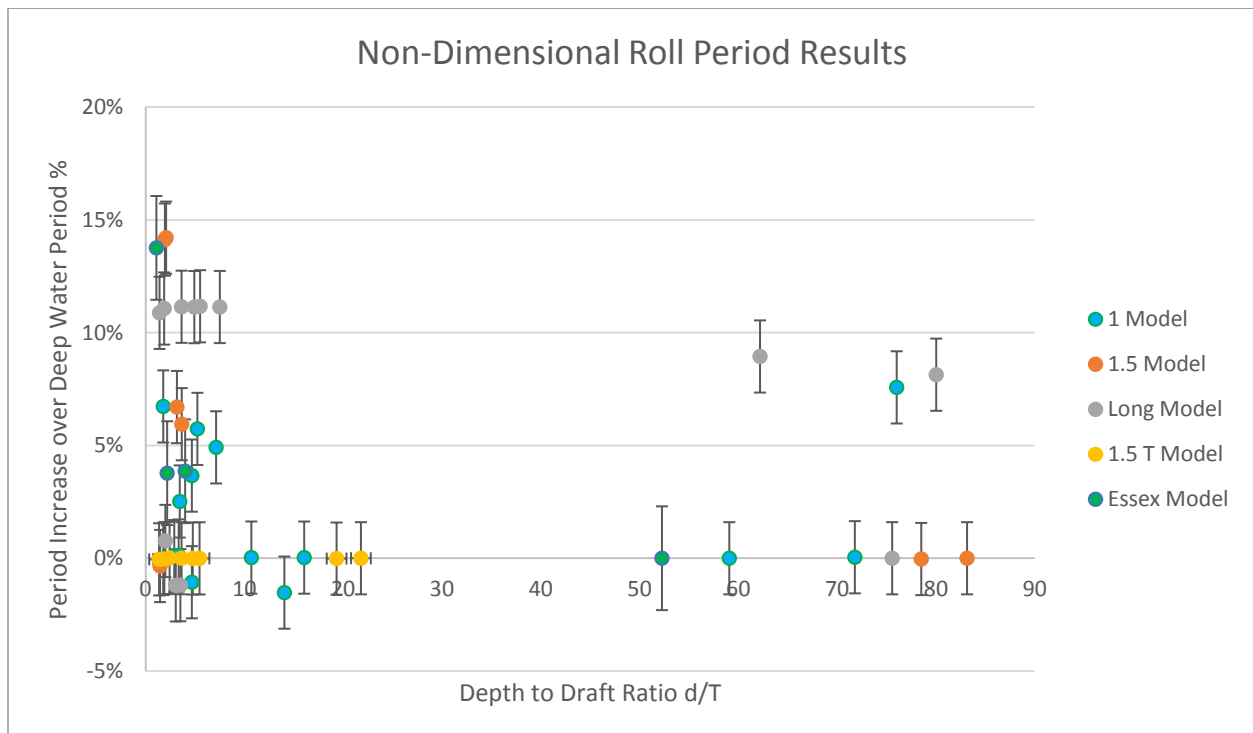
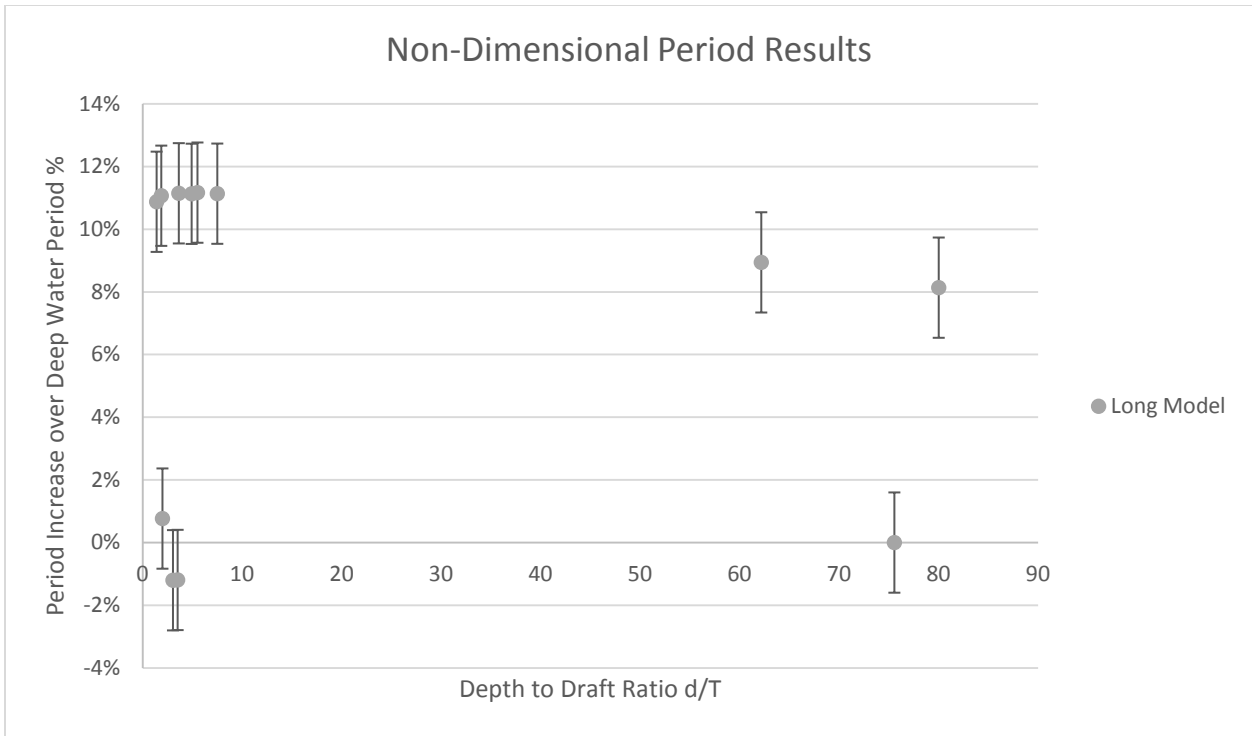
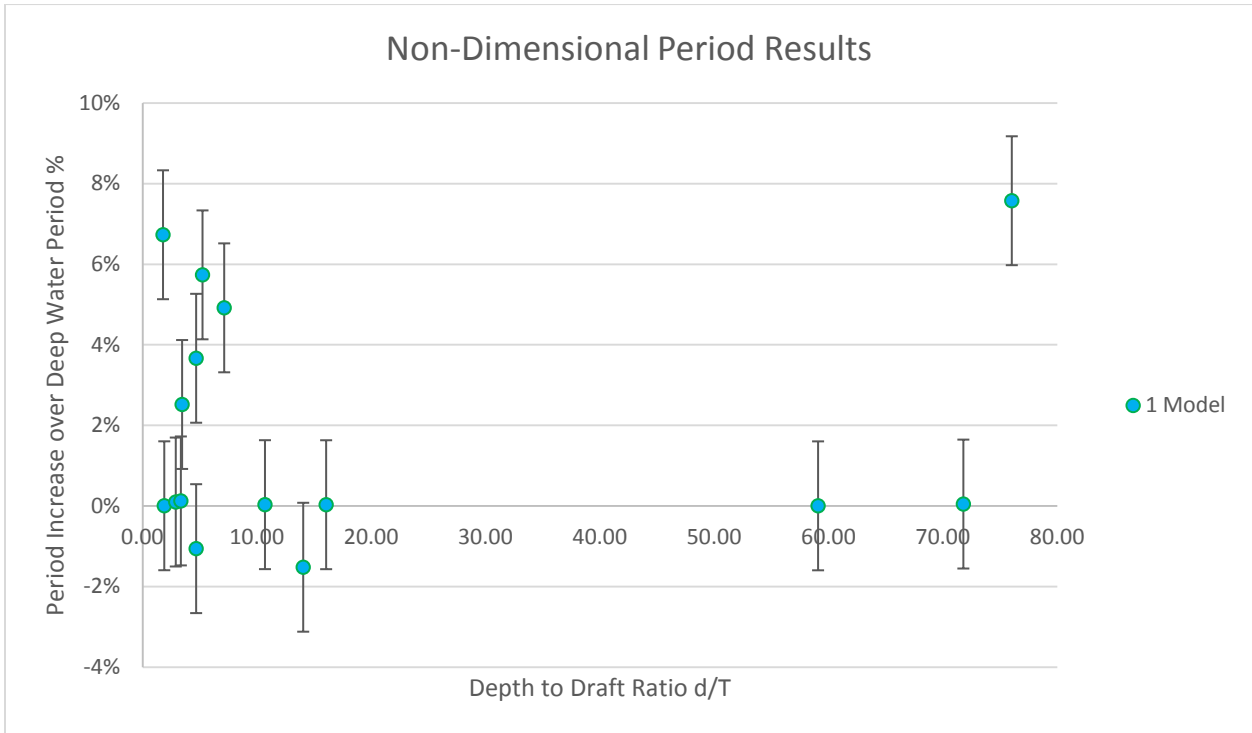


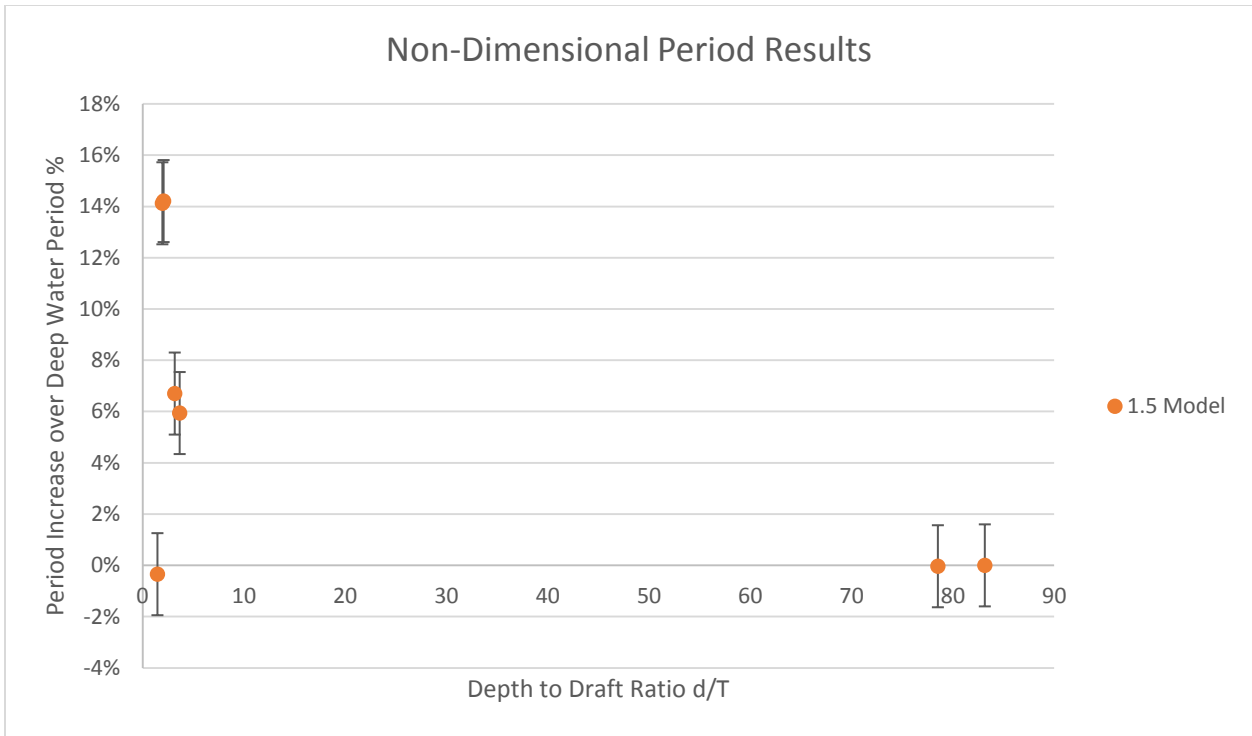
Figure 12: Roll Period Results



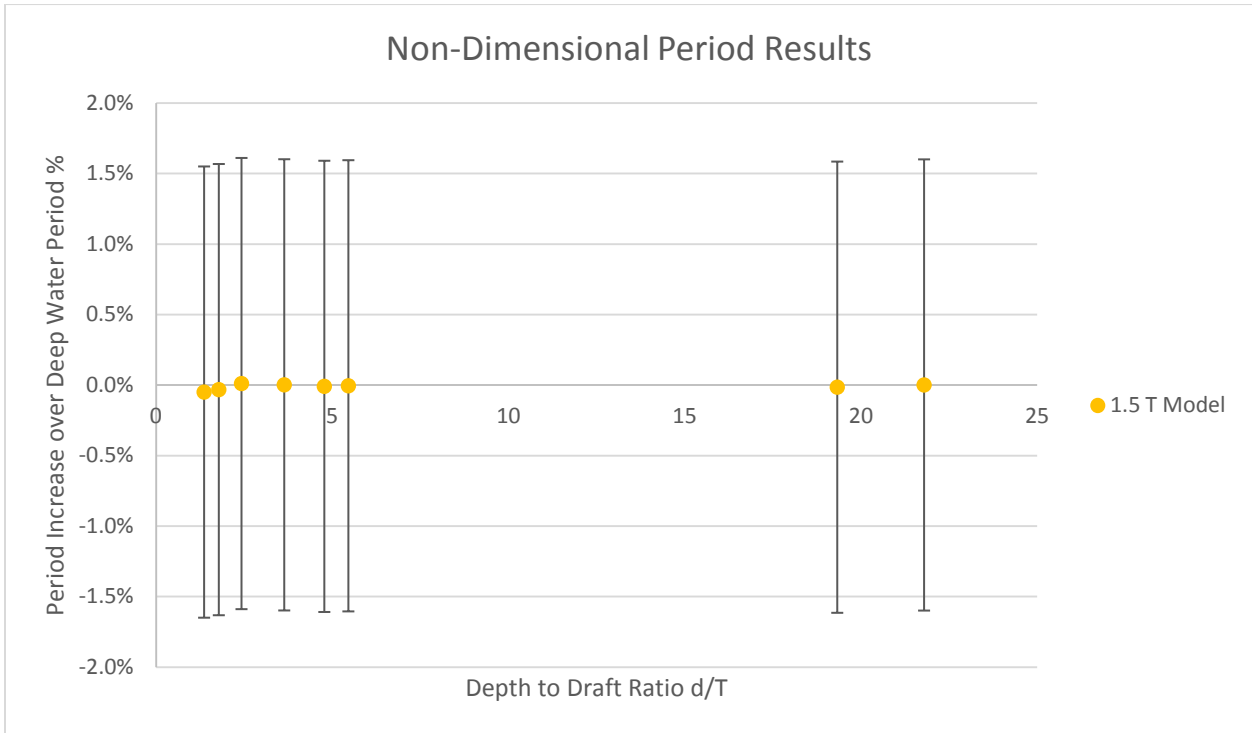
**Figure 13: Long Model Roll Period Results**



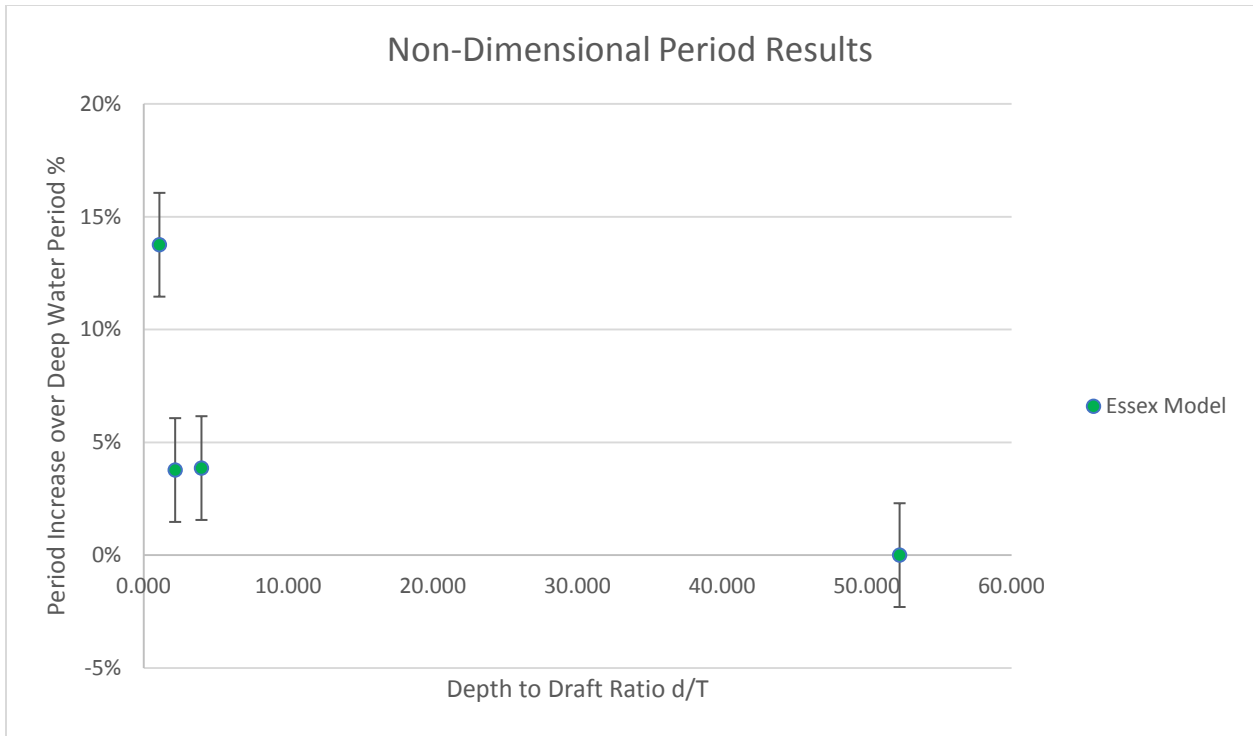
**Figure 14: 1 Model Roll Period Results**



**Figure 15: 1.5 Model Roll Period Results**



**Figure 16: 1.5 T Model Roll Period Results**



**Figure 17: Essex Model Roll Period Results**

The 1 model data for a  $d/T$  of under 3 that do not match expectations were all taken in the summer in the shallow basin (High temperature was  $93^{\circ}$  F that day [36]), while the deep water data points and the other shallower points were taken in the winter (temperature controlled) and spring. If all July data is excluded, as in Figure 18, the roll period plot is closer to expectations. Based on this figure the upper limit on  $d/T$  for “shallow water” for roll period can be inferred to be a little more than 7 depending on the model. For the Essex model and the Long this limit is somewhat greater than 4. A stronger conclusion regarding the location of this limit cannot be drawn because in order to do so a data point that was clearly still in deep water would be needed to bound the issue from the deep water side.

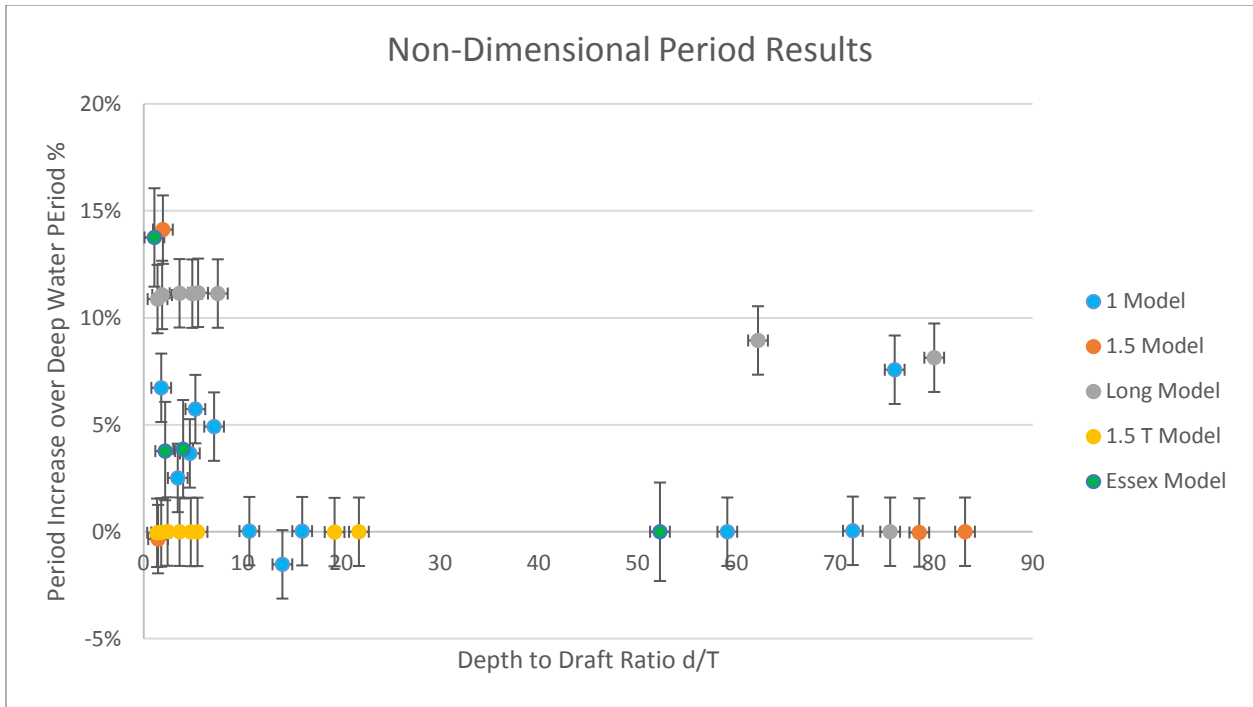


Figure 18: Roll Period Results Excluding July Data

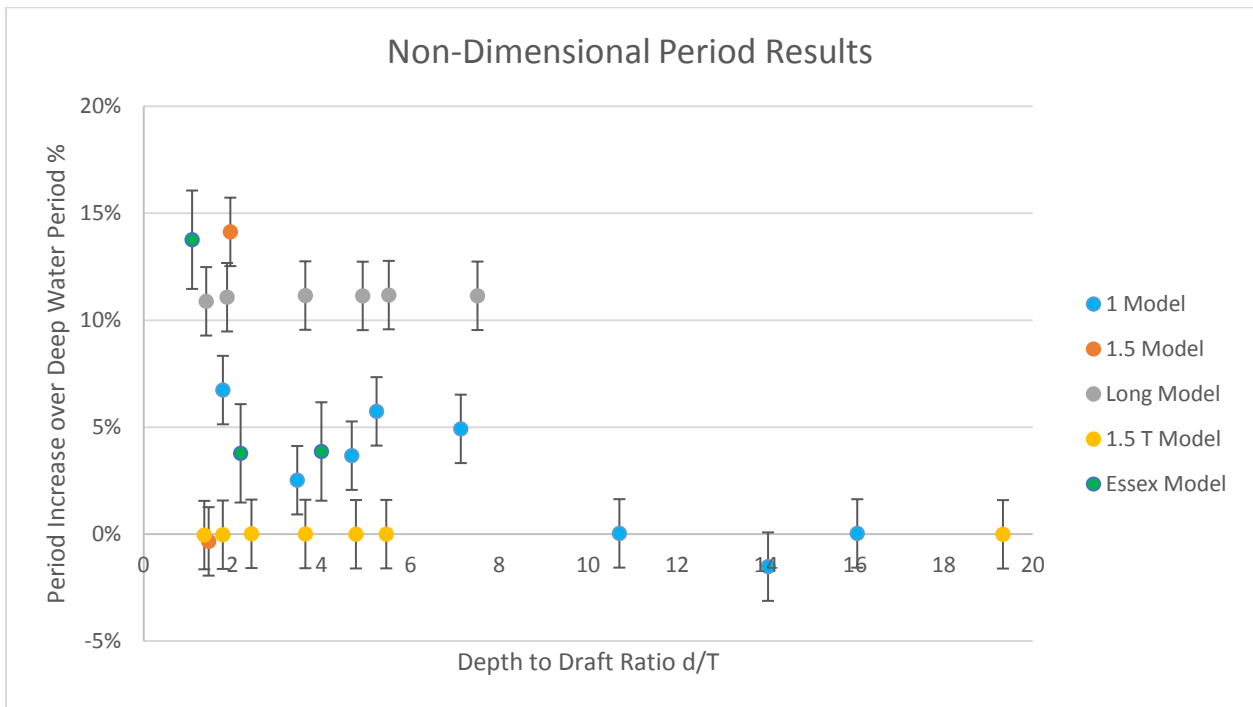


Figure 19: Roll Period Results Excluding July Data Zoomed in on d/T <20

Despite the uncertainty in the results in Figure 18, the roll period data from Inglis and Price [4] and the USS Midway [19] compare favorably. Table 3 compares the Essex Model data with these prior results. While the *Midway* model used by Carderock was presumably several times the size of the Essex model used in these experiments, the results are very similar. The results

are not quite as comparable with Inglis and Price's fine form ship calculations. Incidentally, the *USS Midway* and *USS Essex* have prismatic coefficients of 0.605 and 0.585 respectively and would both also be considered fine form ships. It is a shame more data was not provided about Inglis and Price's ship as this could have allowed for an understanding of how similar the hull forms of the three ships are.

**Table 3: d/T versus Increase in Roll Period**

	d/T	Increase in Roll Period
"fine form ship" [4]	1.10	7.9%
USS Midway Model [19]	2.15	3.4%
Essex Model	1.09	13.8%
Essex Model	2.18	3.8%

## 4.2 Damping

Roll damping directly impacts the rolling period as well as affecting the roll response of a vessel in waves. Thus considering damping is useful both as a way to further understand changes to period as well as to supply data for damping models for motions predictions.

In order to explore the potential causes for the variability in deep water period, the curves of extinction and period data can be compared. Table 4 and Figure 20 allow for this sort of evaluation. Figure 20 shows curves of extinction for the long model in depths of  $d/T = 7.51$ , 62.20, 75.58 and 80.04. The damping of the  $d/T = 62.20$  and 80.04 is virtually identical while the damping for  $d/T$  of 75.58 is greater. Table 4 shows the corresponding roll period for each  $d/T$ . It is notable that while the roll period for  $d/T = 75.58$  is roughly 7% shorter than for the other deep water periods, this depth also has greater damping. It is curious that greater damping results in a shorter period in this case, as increased damping is expected to increase roll period. It is likely that some other factor is affecting the roll period because all other things being equal, damping and period should correlate.

**Table 4: Selected Long Model Period Data**

d/T	FFT Roll Period (seconds)
7.51	0.6040
62.20	0.5921
75.58	0.5435
80.04	0.5877



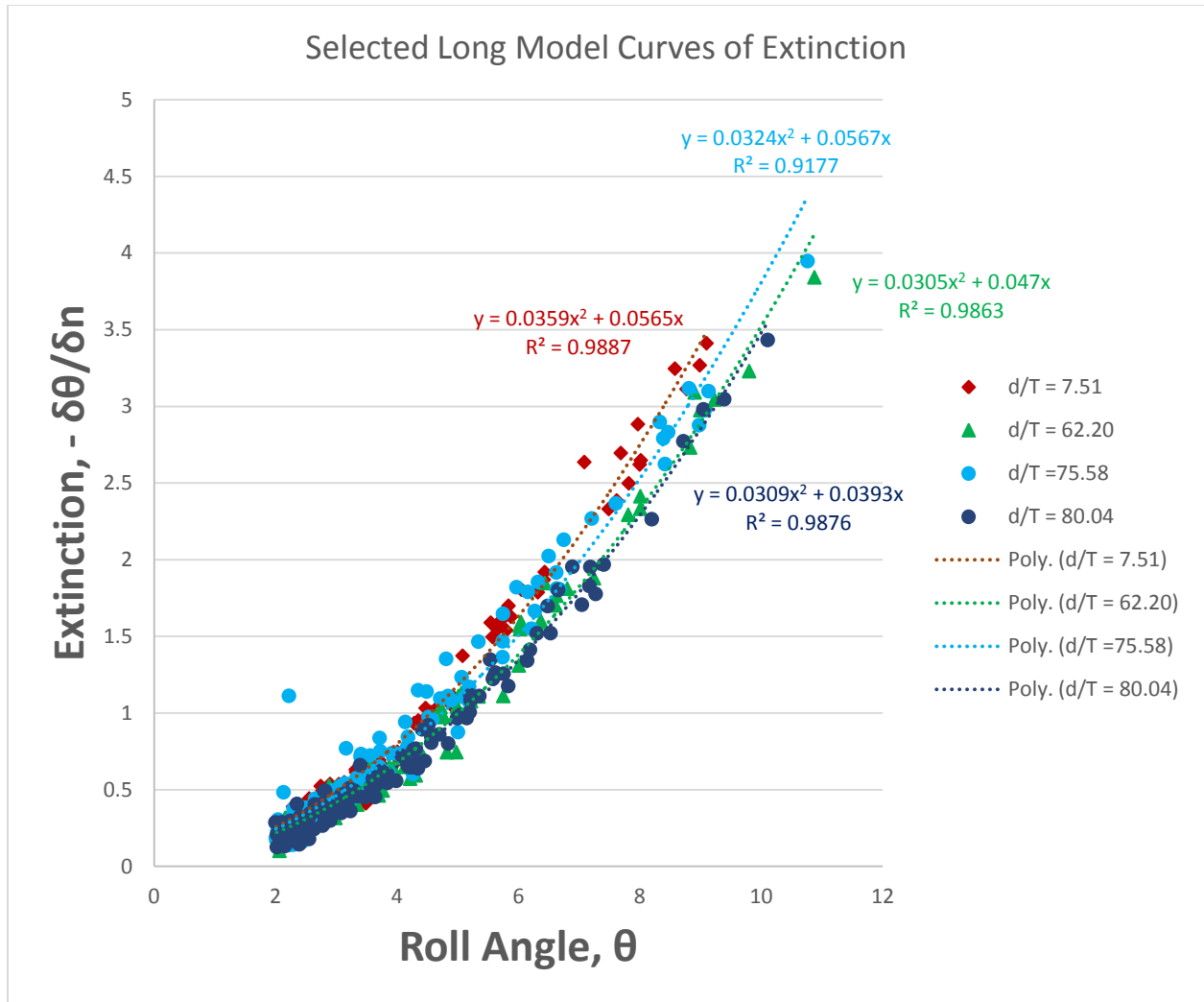


Figure 20: Selected Long Model Curves of Extinction

Figure 21 through Figure 25 provide the curves of extinction for each model for each depth to draft ratio,  $d/T$ , tested. It can be seen that as  $d/T$  trends to unity the damping increases as evidenced by trending away from the x-axis (e.g. greater decrease in roll motions for every roll cycle). The effect appears non-linear.

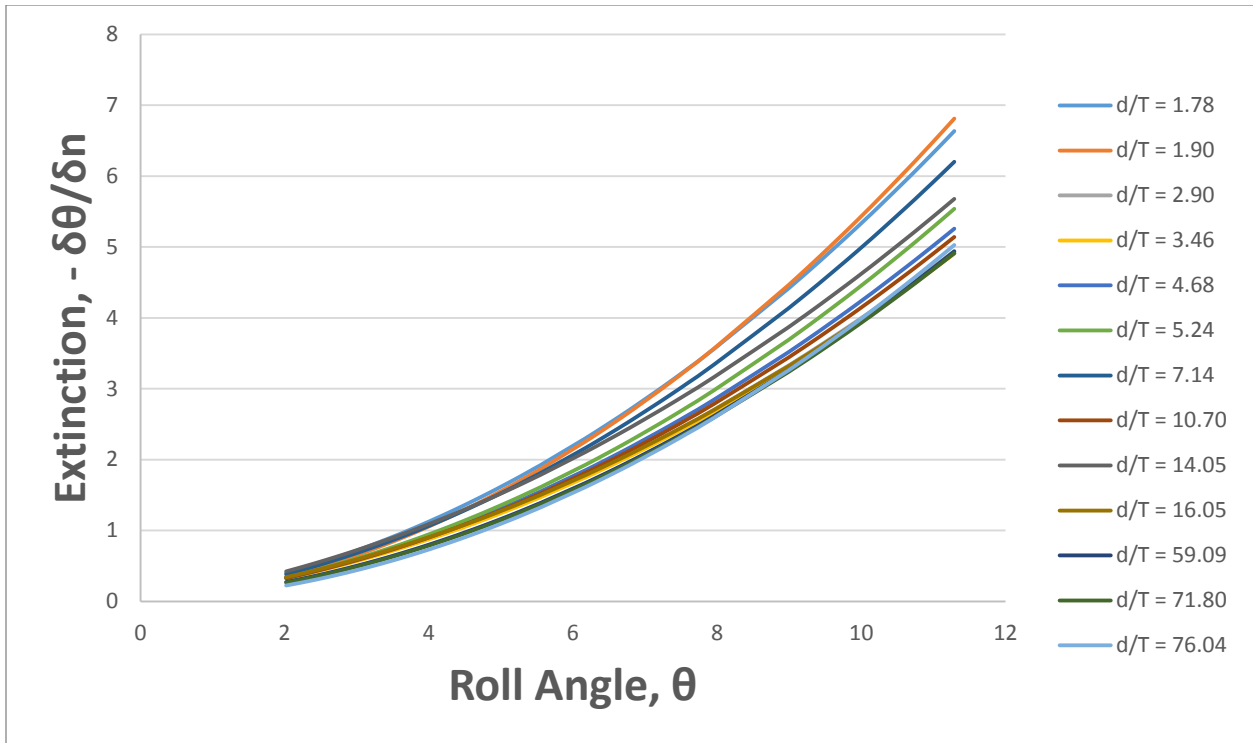


Figure 21: 1 Model Curves of Extinction

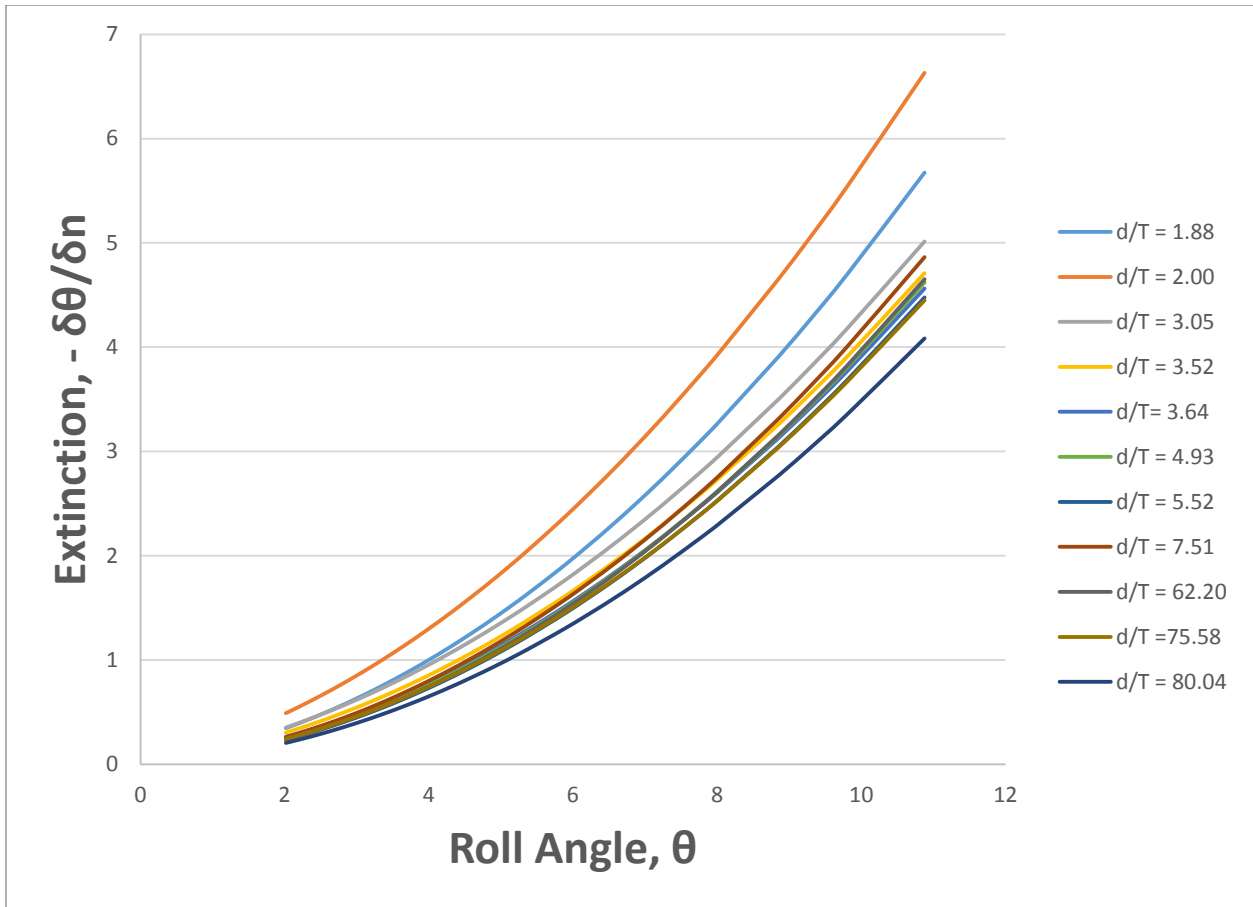


Figure 22: Long Model Curves of Extinction

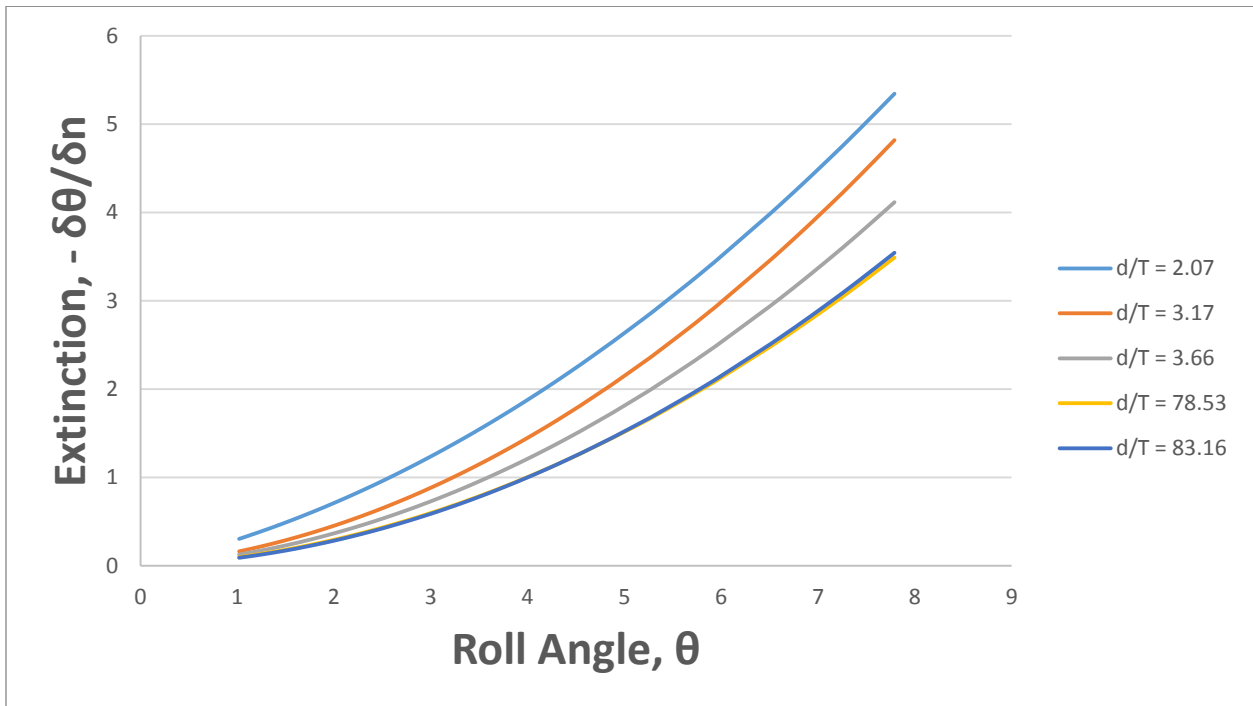


Figure 23: 1.5 Model Curves of Extinction

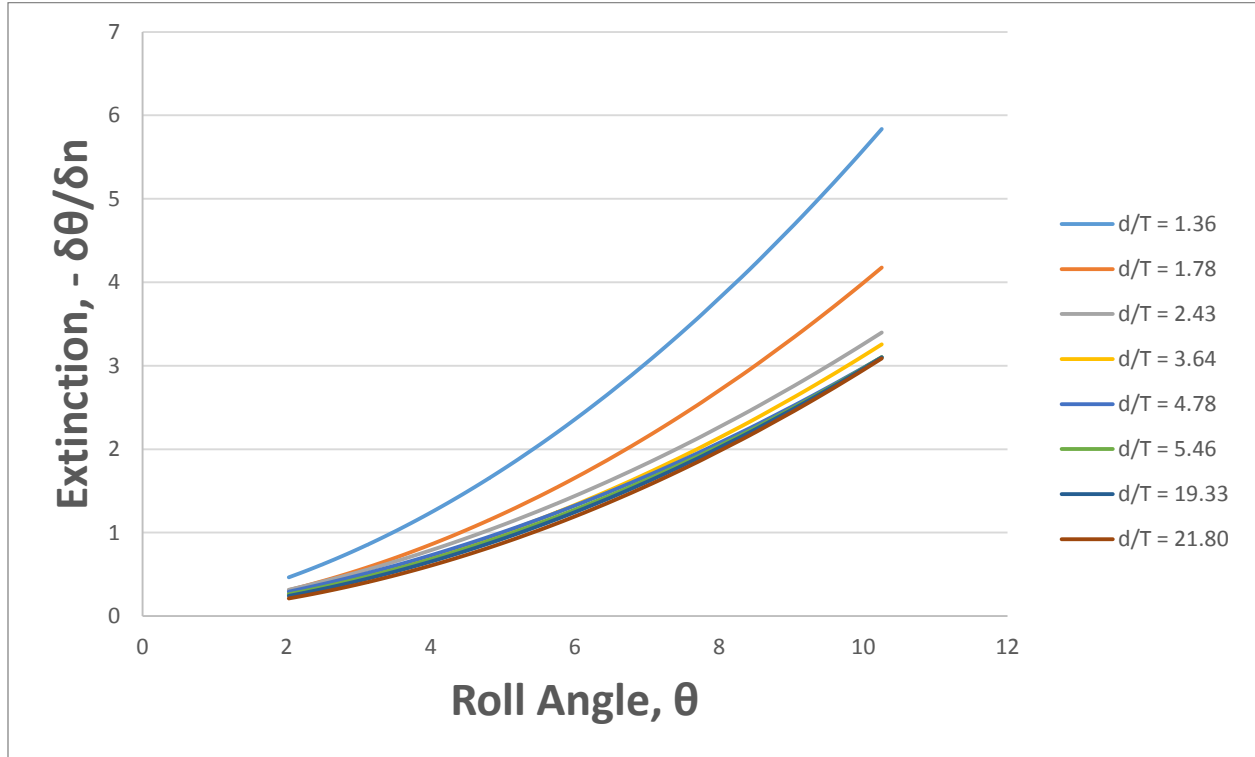


Figure 24: 1.5 T Model Curves of Extinction

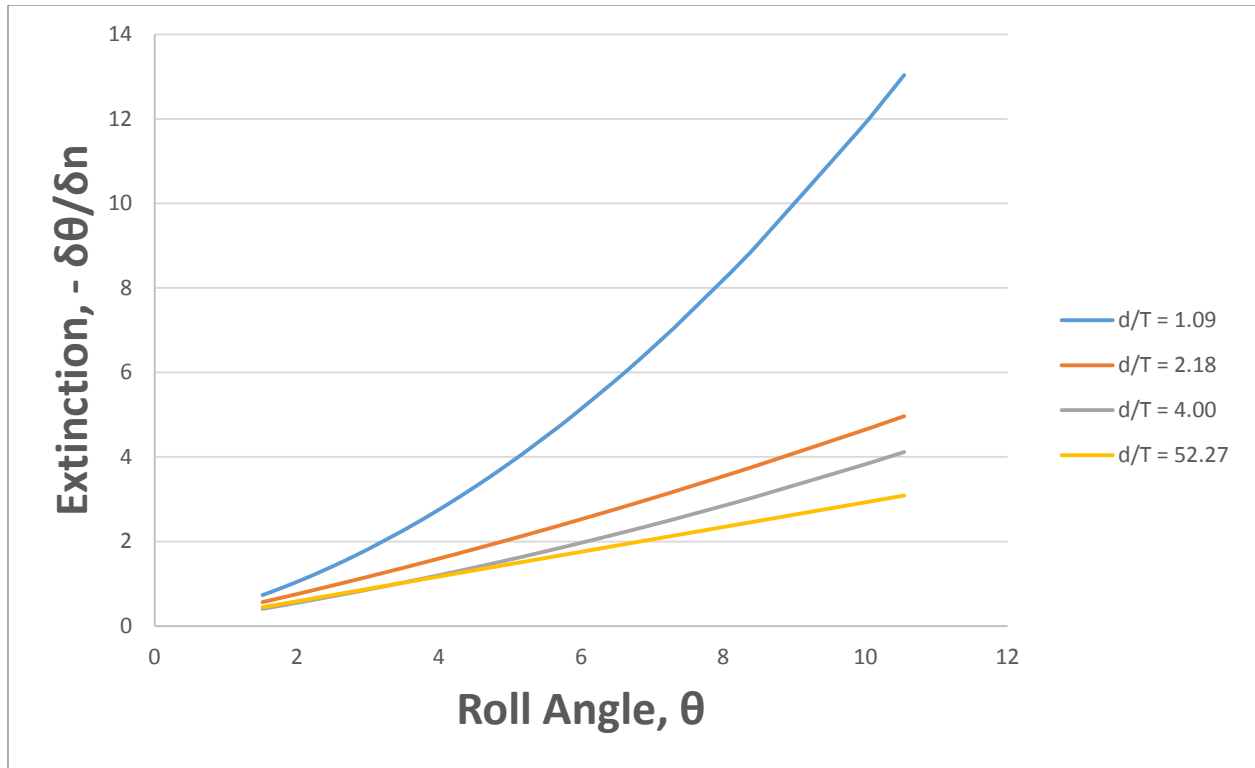


Figure 25: Essex Model Curves of Extinction

The relationships between the curves of extinction at varying  $d/T$  allows for the determination of the upper limit of shallow water. Table 5 lists this limit for each model.

Table 5: Shallow Water Boundary for Roll Damping

Model	Upper limit of Shallow Water for Damping $d/T$
1	>4.68
Long	>3.52
1.5	>3.66
1.5 T	>2.43
Essex	>4

Comparison of the curves of extinction for the 1.5 and 1.5 T models also show that as beam to draft ratio,  $B/T$ , increases, the effect of shallow water on damping also increases. Comparing the increase over deep water damping of the  $d/T = 3.66$  and  $3.64$  curves clearly illustrates this. The 1.5 model has an abnormally high  $B/T$  of 7.32 which probably causes this effect to be overly pronounced.

Gawn [5] found a  $d/T$  of 2.844 to be virtually deep water for his experiments with the *HMS Nubian*, a World War 2 era destroyer. Figure 26 shows the extinction curves Gawn published for this vessel. This is a shallower boundary for deep water than supported by the results in this

study; however, the *HMS Nubian* has a very fine hull form with a midship coefficient of 0.858 and a prismatic coefficient of 0.511 as calculated from the body plan published in [37]. The box barges all have a prismatic and midship coefficient of 1 and the *USS Essex* model has a midship coefficient of 0.980 and a prismatic coefficient of 0.585. The *HMS Nubian* model has much finer hull lines than the models in the present study and this is likely the difference in shallow water effect. Gawn also provided extinction curves for a model of *HMS King George V* in shallow and deep water (shallow water  $d/T = 1.4097$ ) [5]. These results compared favorably with those in the present study. Thus it appears that the fineness coefficients influence both the limits of shallow water and its effect on roll damping.

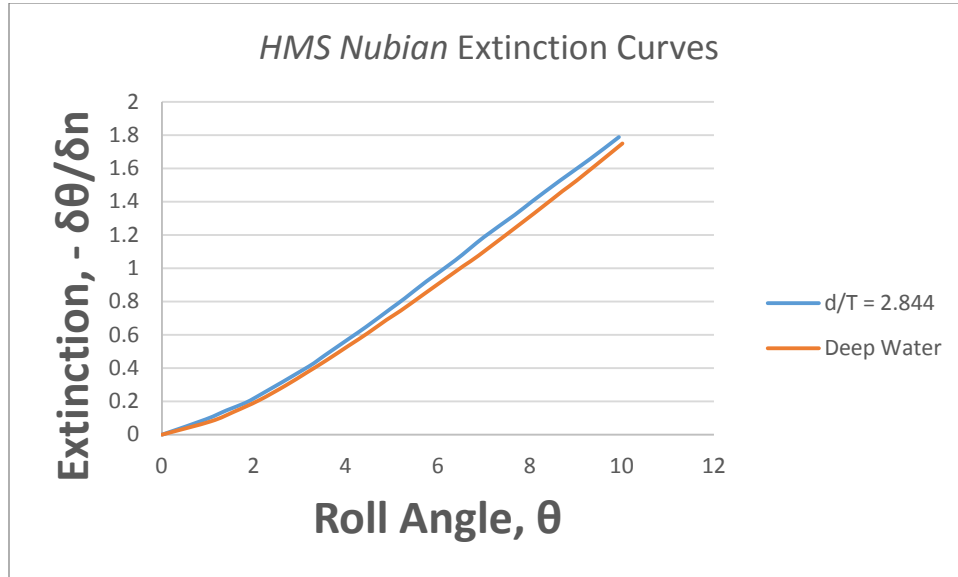


Figure 26: *HMS Nubian* Extinction Curves  $d/T = 2.844$  per Figure 6 of [5]

## 5.0 Conclusions

Roll Period and Roll Damping are effected by shallow water. The boundary between shallow water and deep water is dependent on the qualities of the vessel. This boundary can be as deep as a  $d/T$  of roughly 7. As  $d/T$  trends to 1, the vessel's roll period can increase by as much as 14%. While roll damping is increased for the entire range of shallow water, the increase is particularly pronounced starting at a  $d/T$  of approximately 2. Abnormally high  $B/T$  values cause the shallow water effect to be significantly amplified. The hull form coefficients ( $C_P$ ,  $C_M$  and  $C_B$ ) influence the boundary between deep and shallow water, with fuller forms experiencing greater damping at greater  $d/T$  values. As seen from the results, small models can be used for roll damping and roll period experiments so long as the magnitude of rolling is sufficient to allow for a good signal to noise ratio in the results.

## 6.0 Recommendations for Future Work

This study provides far more data than was previously available on the influence of shallow water on roll period and roll damping. However, there is still significant work to be

accomplished. One ultimate goal of such studies would be the ability to correct the pier side sally test to a deep water result. This would allow for validation of roll gyradius calculations. All of the models in this study have a higher beam to draft ratio than typical vessels although they could be said to represent these vessels in a light condition as is frequently the case pier side. A series of box barges with B/T ratios of 2, 3, 4 and 4.5 would capture the range of normal ship designs and show any influence of B/T on the shallow water effects on roll period and damping. Additionally, a series of models with block coefficients of 0.60, 0.70 and 0.80 would help to quantify the influence the fullness the hull lines has on the shallow water effects on damping.

Using larger models, at least twice as large, would result in better results at the low d/T values where the signal to noise ratio is too low for these small models. It is typical for sally tests to be conducted pier side where the d/T value approaches unity. Due to low signal to noise ratio, there was not much usable data for the determination of the extinction curves at the d/T values approaching 1 in this study. Larger models would improve this. Additionally, using one model basin, in a controlled environment, for all of the experiments would eliminate any unknown sources of error such as differences in the basin floor, walls, and air and water temperature.

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Appendix A: Drawing of Deep Basin [34]

