Wave Wake: Focus on Vessel Operations within Sheltered Waterways

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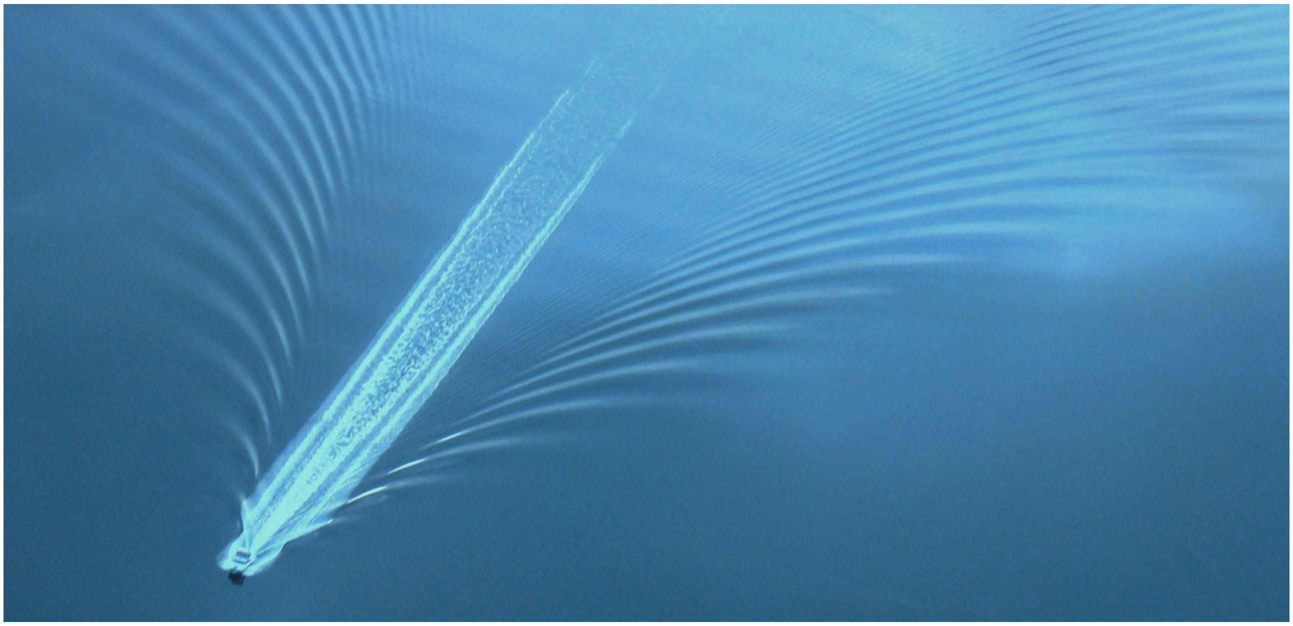

This paper describes the development of an empirical tool that can rapidly and accurately predict the characteristics of the wave wake generated by vessels that typically operate within sheltered waterways, including small commercial craft and recreational vessels. A wave wake regulatory criterion is also proposed and incorporated within the prediction tool.

KEY WORDS: Wash; small craft; high speed craft; recreation; model testing; catamaran; design (vessels).

NOMENCLATURE

B	Waterline beam
d	Vessel draught
Fr_h	Depth Froude number
Fr_L	Length Froude number
Fr_∇	Volumetric Froude number
g	Acceleration due to gravity
h	Water depth
H	Wave height
H_b	Wave height (benchmark)
H_c	Wave height (conventional craft)
H_{HSC}	Wave height (high speed craft)
i_E	Half angle of entry
L	Waterline length
L_{OA}	Length overall
n	Wave decay rate exponent
s	Ship cross-sectional area
s_o	Channel cross-sectional area
T	Wave period
T_b	Wave period (benchmark)
T_c	Wave period (conventional craft)
T_{HSC}	Wave period (high speed craft)
T'	Normalised wave period ($T/\sqrt{L}$)
u_s	Velocity (ship)
y	Lateral distance between the sailing line and measurement point
γ	Wave height constant
Δ	Vessel displacement
∇	Volume
θ	Wave angle (between the cusp locus line and the sailing line of the vessel)

INTRODUCTION

This paper reports on an investigation into the characteristics of the wave wake (also commonly referred to as wake wash or wash) generated by typical vessels that operate within sheltered waterways. It is well known that these waves can result in issues for other users of the waterway and the surrounding environment. These issues include erosion of the surrounding banks, damage or nuisance to moored vessels and other maritime structures and endanger people working or enjoying activities in small craft or close to the shore.

This has led to the increasing need to implement at least one or more of the following remedial measures, Dand *et al*. (1999):

- regulate vessel operations (vessel speed and/or route) within these regions to minimize or eliminate the generation of damaging waves,
- optimize the vessel design to minimize or eliminate the generation of damaging waves; or,
- implement remedial measures on shore.

It appears that the most commonly adopted of these remedial measures for documented cases in sheltered waterways is to regulate vessel operations through the implementation of suitable criteria (Dand *et al.* 1999; Croad and Parnell 2002; PIANC 2003; Phillips and Hook 2006; Osborne *et al*. 2009). Regardless of the actions adopted, there is a demonstrated need to understand the phenomenon and to develop the means to minimize its effect through design and operation.

Over recent decades it has been common for regulators of vessel operations to quantify a vessel's wave wake using the characteristic(s) of just a single wave within the entire wave train, usually the highest. However, Macfarlane (2012) has shown that this is generally inadequate when considering craft operating at trans-critical or super-critical speeds. Three significant waves of interest were described and quantified in this study.

Vessel generated wave patterns are extremely complicated phenomena and various researchers have investigated alternative means of quantifying them. For example, attempts have been made to quantify the overall energy and energy flux of the entire wave train (Gourlay 2010; Kurennoy *et al*. 2009a and 2009b).

The primary aim of this paper is to describe the development and application of an empirical tool designed to provide quick and relatively accurate predictions of wave wake, particularly for vessels operating in sheltered waterways where water depths are limited. The prediction tool utilizes the results from a comprehensive set of model scale experiments conducted to investigate the effect that water depth, hull form and vessel speed has on the waves generated by nineteen different hull forms, including a mixture of typical monohulls and catamarans.

Four primary measures were quantified for each of the three key waves, including wave height, period, decay rate and wave angle. Predictions from the tool were validated against measured data from several independent full scale trials.

A wave wake regulatory criterion, suitable for the operation of typical recreational craft and small commercial vessels operating in sheltered waterways, was proposed and incorporated within the prediction tool.

VESSEL WAVE PATTERNS

The wave pattern generated by a vessel is largely independent of vessel form, but it is affected by water depth, degree of lateral restriction and vessel speed. Traditionally, naval architects and maritime engineers have adopted the length Froude number, Fr_L, to non-dimensionalize vessel speed. When considering vessel operations in finite water depths it is more common to adopt depth Froude number, Fr_h, as it provides a non-dimensional relationship between vessel speed and water depth.

At a vessel speed below a depth Froude number of one, the speed is said to be sub-critical for low s/s_o values. A depth Froude number of one is termed the critical speed and speeds leading up to the critical speed are sometimes referred to as trans-critical speeds (for example, approximately $0.75 \leq Fr_h \leq 1.0$). The boundaries of the trans-critical range can vary according to vessel and waterway conditions and between reference texts on the subject, for example Husig *et al.* (2000) refer to the range of $0.84 \leq Fr_h \leq 1.15$. Speeds above a depth Froude number of one are said to be super-critical. There are many good publications that provide good descriptions of the changes in wave pattern as a vessel moves from sub-critical, through trans-critical and super-critical speeds, for example: Sorensen 1967; Lighthill 1978; Soomere 2007, Robbins *et al*. 2011). A simplified depiction of the wave pattern for each of these speed regimes is provided in Figure 1. Soomere (2007) provides a particularly detailed description of the non-linear components of vessel generated waves.

In the late 1980s, Renilson and Lenz (1989) developed a technique for predicting the wave height at a given lateral distance from a vessel operating in deep water using a limited number of physical model experiments. Prior to this it was impossible to directly and fairly compare different vessels operating in deep water since the interaction of the transverse and divergent components of the sub-critical wave pattern made such comparisons meaningless. This interaction results in vertical fluctuations in the plot of wave height against lateral distance from the sailing line, as can be seen in Figure 2. The method to predict the wave height at different lateral distances, described in more detail in Macfarlane and Renilson (1999), is based on the decay rate of the divergent waves. The technique is to obtain a number of longitudinal wave cuts, and to plot the wave height against lateral distance as shown in Figure 2. A curve of the power form of Equation 1 is then fitted to the experimental data (as shown in Figure 2).

$$H = \gamma . y^{n} \tag{1}$$

Macfarlane and Renilson (1999 and 2000) show that the wave height constant γ can be obtained with good accuracy provided a number of measurements are made in what they have referred to as the 'medium' field – a distance close to the vessel, but outside the so called 'local wave effect'. It is suggested that measurements be made at a minimum of four lateral locations within the region between 1.5L to 3.0L (Macfarlane 2002). Once γ is obtained from the experimental results, Equation 1 can be used to predict the wave height at any given lateral distance from the sailing line. Therefore, the wave height constant γ is independent of this distance and can thus be used to directly and fairly compare one vessel against another.

As shown in Figure 1, there are a greater number of divergent waves generated in the deep water case compared to the case at super-critical speeds, and these sub-critical waves have relatively short crests as the waves emerge and decay. Regardless of these clear differences, the analysis method described above has been adopted for all depth Froude numbers (i.e. sub-, trans- and super-critical speeds). Although not a theoretically precise approach, this method has been shown to provide very good engineering approximations of the primary wave characteristics.

IDENTIFICATION OF THE KEY WAVES

In most texts covering wave dynamics the term 'wave energy' refers to the average over the wave period and that it is simply proportional to wave height squared (H^2). In the present work, wave energy refers to the wave energy density over the duration of a particular wave, thus it is proportional to both wave height and period squared (H^2T^2). This latter description became popular within several publications on the topic of wave wake throughout the 2000s, presumably due to its use as the 'Washington State Ferries' regulatory criterion within the USA (see for example Stumbo *et al.* 1999).

It is very important that the key, or maximum, waves within the entire wave train generated by a vessel are correctly identified and quantified. It has been shown that at sub-critical speeds the maximum (highest) wave generally also possesses the greatest energy of all the waves in the sub-critical wave pattern (Macfarlane 2002). This makes the identification of the single most important wave in the sub-critical wave pattern generally a relatively straightforward task. However, more recent work has concluded that this is often not the case for vessels travelling at trans-critical and super-critical speeds, i.e. the highest wave is not always the wave with the greatest energy (Macfarlane 2012). Thus, it is likely that waves with greater potential to cause bank erosion are ignored. Therefore, it is recommended that more than one wave must be identified when attempting to quantify and assess any vessel wave wake where the waves may be depth-affected. This includes a large percentage of vessels that operate within sheltered waterways.

An investigation has been conducted to determine the minimum number of waves that should be identified and quantified to ensure all potentially significant waves within a wave train are considered. This investigation involved the careful analysis of a very large collection of data obtained through the conduct of model and full scale experiments involving all important variables, each over a wide range of typical 'real-life' conditions. It has been found that clearly identifiable packets, or groups, of waves are often generated, with each packet possessing quite different wave periods (refer Figure 1). Others have also commented on the existence of such packets of waves, particularly from vessels operating at super-critical speeds (for example, Whittaker *et al.* 2000; Doyle 2001; Parnell and Kofoed-Hansen 2001, Soomere 2007).

Following this investigation, it is suggested that in most finite water depth cases there are a minimum of two key waves within each wave train that must be quantified – in simple terms these waves can be defined as those that contain (a) the greatest height, and (b) the longest period, as it is likely that one of these waves will also possess the greatest energy. However, it has been found that there are also a number of cases where a third significant wave is generated which may contain the greatest energy, but not necessarily possess either the greatest height or period. Therefore, it is recommended that the following three divergent waves be defined, identified then quantified:

Wave A – is defined as the leading diverging wave, which is the wave that will possess the longest period (in some situations this may be referred to as a precursor soliton). It is often the waves with long periods that create the greatest issues within sheltered waterways (particularly bank erosion), which makes the quantification of these waves very important. These leading waves are rarely the highest in the wave train, in fact their height is often relatively low, however there are occasions when their height can be considerable (such as when a vessel approaches critical speed), resulting in the potential for transmitting substantial energy to the shore. A long period wave has a long wavelength, so the energy will be large since the sea surface area for the given height is bigger.

Wave B – is defined as the most significant wave following the leading wave (Wave A). The period will be shorter than the leading wave, but often not by a large margin, whereas the height is very often greater than the leading wave. This wave often possesses the greatest wave energy, but may not necessarily be either the longest or the highest wave in the wave train. Although hull form generally does not affect the wave pattern, it has been found that the relative heights of Waves A and B can vary markedly between different hull forms, thus it is advantageous to use experience (familiarity with the wave profiles generated by many different hull forms) when attempting to identify Wave B.

Wave C – it is common for a group of short period divergent waves to be generated and Wave C is defined as being the highest wave within this group. This wave always follows Waves A and B, hence will possess the shortest wave period of these three key waves. In most sub-critical and trans-critical cases this wave also has the lowest wave height of the three waves, or at best a height similar to either Wave A or Wave B (hence also the lowest energy). But what makes this wave significant and worth quantifying is that there are a percentage of occasions, particularly at super-critical speeds, where this wave is the highest generated, and occasionally also contains the greatest energy of all three key waves. However, because of its significantly shorter period, it is very likely that this wave may not be the most significant wave when considering sheltered waterways, as the period may be similar to the local naturally occurring wind wave environment.

The following example is useful to help define each of the above waves and illustrate the need to identify more than one significant wave within a wave train. A typical time series history of a single wave profile obtained from a model scale experiment is shown in Figure 3. In this figure, Waves A, B and C have been identified and the resultant height, period and energy of each wave are provided in Table 1. As can be seen, the highest wave in this example is Wave C, but it possesses the shortest period and a significantly lower energy compared to Waves A and B. In this example, it is the leading wave (Wave A), with the lowest height but longest period, that possesses the greatest energy.

This example highlights the potential dangers when using the commonly adopted wave wake criterion that only considers the highest wave generated when assessing waves generated at trans-critical or super-critical vessel speeds, as it is likely that at least one or two waves with significantly greater energy and longer period may be ignored (potentially many more as Wave B is often representative of a packet of waves possessing similar period). The consequences of this may result in a significant underestimation of the erosion potential of a particular case, or an unfair comparison when attempting to assess various different vessels or other variables. The authors are aware of several occasions where unscrupulous vessel operators have been known to use similar methods to lower the apparent size of the waves their vessel generates when attempting to meet specific regulatory criteria. This is relatively easy to achieve if only a single 'maximum' wave is identified and assessed against a single criterion.

WAVE WAKE EXPERIMENTS

An aim of the present study was to develop a tool that can accurately predict the wave wake characteristics of a wide variety of different hull forms operating over a wide range of vessel speeds and water depths. This tool was developed using data acquired through the conduct of an extensive series of physical scale model experiments. The test program obtained experimental data for a total of 19 different hull forms: 11 of which were monohulls and 8 catamarans, each covering a wide range of length-on-displacement volume ratios ($L/\nabla^{1/3}$), which is a parameter that has been shown to be the single most important when considering wave generation (Macfarlane 2002; Robbins 2004). The hull forms were selected as being typical of many recreational craft and small commercial vessels (between the full size lengths of 5 to 35 m).

The experiments were conducted in the 35 m long by 12 m wide Model Test Basin at the Australian Maritime College in Launceston, Tasmania (AMC 2012). Tests were conducted on each of the 19 ship models at four different water depths; one of which can be considered deep and the other three at finite water depths within the approximate range of $0.15<h/L<0.60$. In each case the tests covered the maximum achievable range of speeds for this facility.

For each of the 950+ runs conducted, wave profiles were obtained using wave probes located at a minimum of six (more often nine) transverse locations, perpendicular to the sailing line of the ship model. This wave surface elevation data was plotted as a function of time for each transverse location (wave probe), and three 'windows' were then manually positioned along the time axis to identify the three waves of interest, Waves A, B and C (as previously discussed and defined), similar to the example shown in Figure 3. Characteristics of these three waves, such as height, period and energy, were determined, as was the time that the peak of each wave occurred within the run. Using this time and the measured speed of the ship model the distance that this peak occurs downstream of the bow of the ship model was determined. These downstream distances for Waves A, B and C at each wave probe were then plotted as a function of transverse distance from the model sailing line, as shown in the example in Figure 4. This plot provides an indication of the shape of each of the wave fronts and can highlight if there have been any obvious errors in the selection of the key waves at each wave probe, as the curve would be discontinuous. The angle θ of each of the three key waves is determined and displayed, and the height, period, time and downstream distances of each wave at each wave probe location are tabulated, as can be seen at the top of Figure 4.

This data was then used to generate plots of the non-dimensionalized wave height from each wave probe as a function of non-dimensional lateral distance from the sailing line. Examples of these plots are provided in Figure 5 for Wave A at two different Fr_h. Both the wave height and lateral distance are non-dimensionalized by dividing by the length of the ship model. By adding a trendline of the power form (Equation 1) the wave height constant γ and the wave decay rate n were determined.

WAVE WAKE PREDICTION TOOL

The tool that has been developed, termed the *Wave Wake Predictor*, is built upon a series of semi-automated look-up tables containing the results from the extensive series of model scale experiments conducted on all nineteen different ship hulls. Predictions of the four key variables of wave height (via the constant, γ), wave period (T), wave decay rate (n) and wave angle (θ) for each of the three waves of interest (A, B and C) are calculated based on several principal vessel and environment details by conducting several look-up and interpolation steps. The required inputs are listed in Table 2. From these inputs, the following parameters and ratios are calculated for the desired case: Fr_h, Fr_L, h/L, ∇, $L/\nabla^{1/3}$.

The *Wave Wake Predictor* can be used to identify significant trends between hull form and water depth, and to provide accurate predictions for a specific type and size of vessel operating at a specified speed and water depth. As covered earlier, determination of the wave decay rate makes it possible to also predict wave characteristics at any lateral distance from the vessel sailing line through Equation 1.

As with any predictive tool, there are limits of applicability that should be applied when using the *Wave Wake Predictor*. To avoid misunderstanding of the results, many of the physical limits within the available data have been built into the tool through the use of checks and warnings. The range of parameters of the *Wave Wake Predictor* have been summarized in Table 3.

A basic version of the *Wave Wake Predictor* is readily available online at http://www.amc.edu.au/maritime-engineering/wave-wake-predictor and its use is free of charge.

Wave Wake Predictor: Application

The *Wave Wake Predictor* can be used to investigate the effect that hull form, as well as vessel speed and water depth, has on the waves generated. As an example, the wave measures of γ and T have been plotted as functions of $L/\nabla^{1/3}$ for each of the three key waves (A, B and C) in Figures 6 and 7. In each of these figures all results are valid for constant input values of $h = 6$ m, $L = 17$ m and $u_s = 16$ knots. From Figure 6 it is clear that hull form has a significant influence on the height of the waves generated, with γ generally decreasing with an increase in $L/\nabla^{1/3}$ for all three waves. A similar result was found by Macfarlane *et al.* (2008). Put simply, these results confirm that wave height can be significantly reduced through the use of relatively long and light vessels.

It is also possible to use the results presented in Figure 6 to compare the relative merits of monohulls and catamarans. In general, catamarans are found to possess a lower wave height constant than a monohull at the same $L/\nabla^{1/3}$. However, this may not be a truly practical comparison given that the relative carrying capacities of a monohull and catamaran of equal $L/\nabla^{1/3}$ are not likely to be comparable.

Hull form has a much lesser influence on the period of the three waves, as can be seen in Figure 7, where there is generally only a marginal reduction in period with increasing $L/\nabla^{1/3}$. There is also less difference between the period of the waves generated by monohulls and catamarans, particularly with the two longer waves, A and B. For this example, and combination of water depth, vessel length and speed, there is a marked difference in the periods of Waves A, B and C. In the vast majority of published cases, where wave wake analyses have only considered the single highest wave, the longest period waves (Wave A) have been ignored, despite the likelihood that they may potentially be the most damaging waves generated.

The decay rate exponent and wave angle for each of Waves A, B and C were found to generally not be affected by changes to $L/\nabla^{1/3}$.

The results presented in Figures 6 and 7 are all for specific values of water depth, vessel length and vessel speed. It is a very simple task to obtain results for other values of each of these variables. This was undertaken in a systematic manner where the general trends identified in the example above were found to be typical for most combinations (within the limits of the prediction tool).

The effect that other basic hull form parameters have on these measures (particularly γ) were also investigated. This included L/B, L/d, B/d and i_E. Only L/B and L/d indicated any predictable relationship with γ. The general trend indicates that an increase in either L/B or L/d will result in a decrease in wave height.

It was found from the analysis of the experimental data that wave height is the only one of the four measures (γ, T, n, θ) that is significantly influenced by hull form, with only a marginal or negligible effect on wave period, decay and angle. It has also been confirmed that the single most important hull form parameter was the length-displacement ratio ($L/\nabla^{1/3}$). This agrees with the work of Yih and Zhu (1989a, 1989b), who proved mathematically that, under ideal conditions, the wave period and angle are solely defined by Fr_h and any deviation from the theoretical values would be due to secondary effects.

In coastal engineering terms, energy states tend to jump in orders of magnitude, not in incremental percentages. In many respects the push by designers to improve the wave wake characteristics of their vessels by a nominal modest percentage is likely to be somewhat inconsequential in bank erosion terms. Generally, a vessel design either will or will not be acceptable – small changes to design parameters such as waterline beam, draught and angle of entrance are unlikely to turn a design that causes excessive erosion into an acceptable one.

Predictions of the wave wake characteristics of a specific vessel (either monohull or catamaran) can be provided simply by inputting the desired vessel length and displacement, in addition to the water depth and vessel speed for the proposed operation. Predictions are made by conducting another look-up and interpolation within the *Wave Wake Predictor*, this time using the desired vessel length and displacement to calculate the resultant $L/\nabla^{1/3}$.

The data presented in Figure 6 can be used to demonstrate this process. If the length and displacement of a proposed monohull are 17 m and 12 t respectively, the resultant $L/\nabla^{1/3}$ will be 7.5, indicated in Figure 6 as a small (red) tick along the x-axis. An interpolation is conducted between the data for the monohull models just below and above this value of $L/\nabla^{1/3}$ (6.91 and 7.78 in this example) for each of Waves A, B and C. A similar routine is conducted to obtain predictions for the other wave measures of T, n and θ although as confirmed earlier, these measures do not vary as much with changes in $L/\nabla^{1/3}$. The resultant predictions for this single speed example are provided to the user in tabular form.

It is often useful to obtain predictions at many different vessel speeds, or water depths, hence a means of obtaining such data has been incorporated into the full version of the prediction tool. For example, the resultant wave height for a monohull of $L = 17$ m and $\Delta = 12$ t operating in $h = 6$ m water depth at $y = 20$ m is plotted as a function of speed for the approximate range of $0.35 < Fr_h < 1.60$ in Figure 8. Plots of wave period, decay and angle as functions of Fr_h for the same conditions are shown in Figures 9, 10 and 11 respectively. Similar plots can be readily provided for other forms of speed measurement, including: Fr_L, Fr_∇ and full scale speed (knots).

In Figure 9, it is clear that the period of Waves B and C remain relatively constant at higher speeds (in this case at speeds where $Fr_h > 1.2$). The period of Wave A, however, continues to reduce at these higher speeds.

Wave Wake Predictor: Validation

Proof of the applicability, or validation, of the *Wave Wake Predictor* has been investigated through the comparison of its predictions against wave wake data collected from several series of full scale trials conducted on various different types of hull form on several different sheltered waterways.

The success of field trials is highly dependent on having rigorous and time-proven testing methodology, instrumentation and analysis procedures. Vessel wave wake is not a steady-state phenomenon (from a fixed reference frame) and its assessment is reliant on consistency.

The testing methodology adopted for this study ensured that the results were not site-specific and can be transposed with other results from other sites. Full-scale experiments are often subjected to many natural and procedural influences that affect the accuracy of the results. Besides complications such as wind waves, currents, and variable water depths, other influences must be tempered to improve accuracy and repeatability. The most important issues are covered in detail by Macfarlane and Cox (2007).

Full scale trials were conducted on a 24 m L_{OA} catamaran over a range of sub-critical, trans-critical and super-critical speeds. Further details on these full scale trials and corresponding model scale tests are provided in Macfarlane (2009). The full scale wave heights and periods of Wave A for this vessel are presented as functions of Fr_L in Figures 12 and 13 respectively. Three sets of data are presented in each of these figures, including the full scale trials data, predictions from model scale test results and predictions from the *Wave Wake Predictor*. The model scale tests on the 24 m catamaran were conducted and analyzed independently from those used to develop the prediction tool, so, like the full scale trials data, are also suitable for validation purposes.

Uncertainty analysis has been conducted on both the model and full scale measurements to determine if the variation in results was within the predicted accuracy. The uncertainty limits are presented using error bars in Figures 12 and 13.

As would be expected for tests in an uncontrolled environment, there is a reasonable degree of scatter in the full scale trials data. However, there is good correlation in all cases as the predictions from the *Wave Wake Predictor* generally fall within the estimated limits of uncertainty for both the full scale data and the independent predictions from model scale experiments, as illustrated in Figures 12 and 13.

In addition, the acceptable level of agreement between the predictions based on the independently conducted model scale tests and the full scale trials data confirm that a correlation factor of close to unity be applied when using model scale experimental data to predict full scale wave heights and periods for similar vessels operating within the range of depth and length Froude numbers. This is consistent with results found in Macfarlane (2006) and (2009).

Similar plots to those shown in Figures 12 and 13 are provided in Macfarlane (2012) for the wave heights and periods of Waves B and C, where a similar degree of correlation was found.

The full scale trials results presented here (Figures 12 and 13) originate from the same raw data as those presented in Macfarlane (2009), but the data has been reanalyzed to obtain the wave heights and periods for all three waves of interest (A, B and C). As discussed previously, it is not uncommon to find more than one significant wave in a wave pattern that should be identified and assessed, particularly for vessels operating at super-critical speeds (such as the example provided in Figure 3). Results presented by Macfarlane (2009) identified two distinct packets of waves, each packet with quite differing wave periods, but with the short-period wave being the highest. For the higher speeds, around $0.8 < Fr_L < 1.0$ (where the Fr_h are super-critical), it was found that the periods of the groups of long and short waves were approximately 4.0 s and 2.0 s respectively. The relevant figure from Macfarlane (2009) has been reproduced here in Figure 14 (note that this figure shows more full scale data than that visible in Figures 12 and 13 - only 50% of the full scale runs were reanalyzed in the present study as this was deemed to be more than adequate for comparative purposes). It can be seen that the period of 4.0 s corresponds with the data for Wave B in the present analysis and the period of 2.0 s corresponds with Wave C. Importantly, at each of the speeds in this range the highest wave was consistently Wave C. This highlights a major flaw in the commonly adopted criteria that only assesses the highest wave generated, as in these cases Waves A and B would have been ignored, but both can be much more damaging to sensitive shorelines due to their much higher periods.

Further examples of the validation of the *Wave Wake Predictor* are presented in Macfarlane (2012), where predictions are compared against full scale data for a 29 m catamaran, several ski boats, an 8.2 m L_{OA} water bus and a 7.75 m L_{OA} aluminum runabout.

It should be noted that a vessel's propulsion system, regardless of type, is likely to contribute to the height of some of the waves generated. An increase in height of the maximum waves of up to 10% appears to be a reasonable approximation, Leer-Andersen and Lundgren (2001). The full scale trials data presented in Figures 12 to 14 will include any contribution from the propulsion system, however the predictions do not.

WAVE WAKE REGULATION

It is required that regulatory criteria appropriate for the operation of recreational and small commercial vessels operating in sheltered waterways need to be identified. Australia has a relatively large recreational boating population that utilizes the limited sheltered waterways available. This is not dissimilar to the USA, where the majority of recreational boating is enjoyed on fresh water lakes and rivers, as well as sheltered coastal waterways, rather than the open ocean. It therefore makes sense to attempt to develop guidelines for vessel wave wake that allow for the sustainable use of these waterways.

To date, the development of vessel operating criteria for mitigating foreshore impacts has been largely vessel and/or site-specific, making transposition of operating criteria between different sites almost impossible. This is thought to be due to the response of research and regulatory bodies being highly reactive in their approach to wave wake and erosion and as such has been characterized by pockets of site-specific research with little attempt at standardization (Macfarlane and Cox 2007). A partial exception are the Gordon River cruise services in Tasmania, Australia, which, operating within a National Park and World Heritage Area, are regulated by a land management rather than maritime agency. There the initial response in the early 1990s was reactive, but became proactive with the implementation of a long-term monitoring and vessel certification process that is on-going today (Bradbury *et al.* 1995; Bradbury 2007).

In order to develop wave wake criteria, certain simplified parameters that characterize a vessel's wave wake must be used; otherwise the total range of variables may prove too large to be of practical use (Nanson *et al.* 1994; Macfarlane and Cox 2004). However, many existing wave wake criteria are based on over-simplified concepts and may provide only limited protection against foreshore erosion. From a review of wave wake criteria in use worldwide, older methods that relied on wave height alone are being superseded by measures involving both wave height and period (Macfarlane and Cox 2007). This reflects the growing understanding that both are major determinants of wave wake severity. The most poignant example of this are the "Wash Rules" of both Denmark and New Zealand which have been in place for over a decade, Parnell and Kofoed-Hansen (2001). This criterion is shown in Equation 2.

$$H_{HSC} \le H_C.(T_C / T_{HSC})^{1/2} \qquad (2)$$

The subscript $_{HSC}$ refers to the height and period of high speed craft and subscript $_C$ to conventional craft.

The *Wave Wake Rule*

It is suggested that wave wake criteria appropriate for regulating vessel operations on sheltered waterways be based upon a variant of the concept originally formulated for operation of large high speed craft operating in Danish and New Zealand coastal waters (Parnell and Kofoed-Hansen (2001). The proposed criterion is shown in Equation 3:

$$H \le H_b\,(T_b/T) \qquad (3)$$

where both H_b and T_b are benchmark values (constants) and appropriate values should be determined to suit the site-specific conditions. This approach (as shown in Equation 3) is referred to as the *Wave Wake Rule.*

The benchmark values for wave height and period in Equation 3, H_b and T_b, can be determined through one of several methods, with the primary aim to identify the threshold below which the impact of vessel wave wake no longer presents an issue for the region of concern.

An ideal example to illustrate one method is from the original application of the Danish and New Zealand criteria, where Parnell and Kofoed-Hansen (2001) measured the 'acceptable' waves of conventional ferries already operating on the route of interest. The benchmark values in this case were H_b = 0.5 m and T_b = 4.5 s.

An example of another suitable method for determining appropriate benchmark values is through the conduct of on-site measurements of the rate of erosion, such as the experiments described in Macfarlane *et al.* (2008) where the turbidity near the shore resulting from vessel wave wake was measured. In this case the benchmark values where bank erosion was found to be minimal or negligible for the lower Gordon River in Tasmania, Australia, were determined to be H_b = 70 mm and T_b = 1.0 s.

These elevated turbidity results are plotted, along with the *Wave Wake Rule* using these benchmark values in Figure 15, where wave height is plotted as a function of wave period. The intention is that the height and period of each of the three significant waves (A, B and C) generated by a vessel (at a specific speed and lateral distance) must lie below the *Wave Wake Rule* to indicate that minimal or no erosion (turbidity) will occur.

A further example of an alternative method for the determination of appropriate benchmark values is through comparison with the natural wind wave climate. Sheltered shorelines in a wind wave environment are often dynamically stable and beach areas adjust in response to the prevailing wave climate and sediment budget. As a result, several studies have attempted to assess vessel generated waves by comparing their energy (over the duration of a particular wave) against those of the local wind waves (Soomere and Rannat 2003; Kelpsaite *et al*. 2009; Houser 2010). Wind wave data can be estimated by hindcasting given the wind speed and fetch and using standard formulae such as those detailed in USACERC (1984).

In summary, three methods that can and have been used to determine appropriate benchmark values for application with the proposed *Wave Wake Rule* have been provided, including (a) the characteristics of waves generated by vessels that have proven through successful operation that they generate an acceptable wave wake, (b) direct measurement of erosion caused by passing vessels, and (c) comparing against the characteristics of wind-generated waves that naturally occur in the region (either through hind-casting or measurement). Other possible methods may also exist.

Wave Wake Predictor and *Wave Wake Rule*

The assessment of wave wake can be streamlined by combining the predictions of all three key waves from the *Wave Wake Predictor* (Waves A, B and C) with the regulatory criteria provided by the *Wave Wake Rule*. By considering each of these waves it is assured that all potentially damaging waves will be assessed, which was not possible with many of the assessment processes currently in use that consider just a single significant wave.

For instance, some high-speed vessels, particularly those that claim to possess “wave wake reducing characteristics” (which are more strictly often only wave height reducing characteristics by way of high length-displacement ratio) have the potential to satisfy an apparently reasonable criterion but still cause erosion. Prime examples of this are the various “low-wave wake” catamaran ferries operating on the Parramatta and Brisbane Rivers in Australia. Such vessels have been found capable of generating wave periods considerably in excess of the existing waterway wave climate (up to 4-5 times longer), but with low accompanying height when travelling at high speed. It is likely that these low but long-period waves would not have been assessed in any scenario that only assesses a single maximum wave.

An example of this is illustrated graphically in Figure 16 where the *Wave Wake Rule* is plotted along with the predictions from the *Wave Wake Predictor* for the 24 m catamaran discussed earlier (and by Macfarlane 2009) where full scale trials data for this vessel was used as part of the validation process. In Figure 16, wave height is plotted as a function of wave period and the curve for the *Wave Wake Rule* based on benchmark values of H_b = 450 mm and T_b = 2.5 s. The three significant waves (A, B and C), generated by the 24 m catamaran at the supercritical speed of Fr_h = 1.11, as predicted by the *Wave Wake Predictor* are shown. In this example the Fr_L = 0.83, h/L = 0.55 and y/L = 1.38.

The significant feature of Figure 16 is that Wave C for the 24 m catamaran – the highest wave – lies below the *Wave Wake Rule*, indicating that it meets the criteria, however both Waves A and B for this vessel clearly exceed the same criteria. This example confirms that current wave wake assessment methods based on just a single maximum wave cannot ensure that all potentially damaging waves within a wave train will be assessed. Subsequently, this may result in the occurrence of the various wave wake related problems previously discussed.

The identification of the three significant waves, including the longest, highest and maximum energy waves, combined with the use of such wave wake criteria (with benchmark values appropriate for the region of interest) will ensure that these problems are avoided or minimized.

Also included in Figure 16 are predictions for other monohulls and catamarans of varying $L/\nabla^{1/3}$ from the *Wave Wake Predictor* (all scaled to have the same L as the 24 m catamaran and travelling at the same speed and lateral distance and in the same depth of water). This illustrates that there are many hull forms that can meet this same criteria under similar circumstances, as well as many that fail by an even greater extent. It should be noted that this does not necessarily mean that the vessels of alternative $L/\nabla^{1/3}$ can meet the desired load carrying capacity.

Another example where the combined application of the *Wave Wake Predictor* and *Wave Wake Rule* can assist in a scientific assessment of the likely impacts is with the issue of recreational activities such as water-skiing and wake-boarding being conducted in regions with sensitive shorelines. This is a commonly occurring issue within Australia (and overseas), particularly within rivers and estuaries close to population centers (Watkins 2004; Cameron and Hill 2008).

Each of the studies listed above involve locations where the fetch is very limited so they can be considered as ‘low energy’ environments, but their shorelines would be expected to be dynamically stable and accustomed to the naturally occurring wind wave environment. In order to illustrate how the fetch can affect the characteristics of the wind waves, the benchmark values for the curves of the *Wave Wake Rule* for three different scenarios are plotted in Figure 17. The values for H_b and T_b for fetch distances of 100, 500 and 1,000 m and constant wind velocity of 10 m/s have been obtained from hindcast wind wave data. As expected, as the fetch reduces so does the wind wave height and period, hence also each of the curves from the *Wave Wake Rule*.

Also shown in Figure 17 are the predictions of Waves A, B and C from the *Wave Wake Predictor* for a typical ski boat. Data is provided for the four vessel speeds of 12, 17, 22 and 30 knots, with each of these being representative of typical speeds for certain activities. For example, 17 knots is commonly adopted by wake-boarders, 22 knots is a typical speed for water-skiing (particularly using two skis), 30 knots is more common for slalom skiing (single ski), barefoot skiing and jump skiing, while 12 knots is sometimes used for slow speed trick skiing.

It can be seen that when the speed of the ski boat is increased the period of the longest wave, Wave A, decreases significantly and its height gradually reduces. In contrast, the period of Waves B and C only reduces very marginally, or not at all, but the heights of these waves reduce significantly as speed is increased. This concurs with the predictions from the *Wave Wake Predictor* given in Figure 9.

By comparing the predicted waves with the three different criteria curves, each representing the different fetch distances, it is clear that the activities conducted at the slower speeds, such as wake-boarding, should only be conducted in regions of relatively long fetch (in the order of 1,000 m) if excessive shoreline erosion is to be avoided, or the activities should be conducted at greater distances from sensitive shorelines (which may not be possible in narrow rivers). Ski boat operation at the higher speeds (22 and 30 knots) is less likely to generate damaging waves and thus can be undertaken in more fetch-limited regions.

Another important factor that should be taken into consideration is that the ski boat data provided in Figure 17 relates to constant speed in a straight line, but it is common for such water sports to involve regular stopping, starting and turning. As any boat accelerates, or decelerates, through the various speed regimes it will obviously pass through those zones when larger, more damaging waves may be created. The result described by Torsvik *et al.* (2006) is of interest here, as they found that it is possible to almost avoid generation of high waves for accelerating ships, but virtually impossible when a ship's speed decreases from a super-critical to sub-critical speed.

CONCLUSIONS

The quantification of wave wake generated by marine vessels operating in sheltered waterways has been investigated to provide an accurate and rapid method to determine, at design and planning stages, whether damaging or dangerous waves will result.

In this work it has been demonstrated that the identification and quantification of just a single wave for finite water depth conditions, which has generally been accepted practice in recent decades, is inadequate at identifying all potentially damaging waves within a vessel generated wave train. It is recommended that at least three waves be considered, which must include the highest and longest waves generated, and the wave with the highest energy.

Experimental data has been analyzed to determine the four primary parameters of wave height constant, wave period, wave decay exponent and wave angle for each of the three significant waves. This analysis has confirmed that finite water depth can affect these three waves very differently: the leading waves, which possess the longest period, are significantly altered, with large changes occurring to all four wave parameters between sub-critical, trans-critical and super-critical speeds. A much lesser, and in some cases negligible, effect was found for the other two key waves, because the period of these waves is too short for the limited depth to have any noticeable effect. As expected, the characteristics of all three waves were confirmed as being very dependent upon vessel speed.

A *Wave Wake Predictor* has been developed that can predict the primary vessel wave wake characteristics for vessel operations at sub-critical, trans-critical and super-critical vessel speeds. This tool has been specifically developed to deal with typical vessels that operate in sheltered waterways where bank erosion is a potential issue.

The accuracy and reliability of the *Wave Wake Predictor* has been proven through a validation process that involved the comparison of predictions against full scale data from several different hull forms operating at various water depths and vessel speeds. The benefits of identifying and quantifying the three key waves were highlighted during this validation process, as previous analysis of this full scale trials data (by the authors) concentrated only on the single highest (maximum) wave, but this was found not to be the most damaging wave under certain conditions.

Attempts by vessel designers to improve the wave wake characteristics of their vessels by a nominal modest percentage is likely to be somewhat inconsequential in terms of reducing bank erosion. Generally, a vessel design either will or will not be acceptable – small changes to design parameters like waterline beam, draught and angle of entrance are unlikely to turn an erosive design into an acceptable one.

A regulatory criterion that is considered appropriate to the operation of typical recreational craft and small commercial vessels operating in sheltered waterways has been proposed. The *Wave Wake Rule* requires the input of two benchmark values, which can be determined through one of several methods. The primary aim is to identify the threshold below which the impact of vessel wave wake no longer presents an issue for the region of concern.

The *Wave Wake Rule* can be used with the *Wave Wake Predictor* to determine appropriate guidelines for acceptable vessel operations and assess the potential reduction in bank erosion directly related to vessel wave wake. For example, a case study was undertaken to assess the likely impacts of recreational activities such as water-skiing and wake-boarding in fetch-limited regions where low-energy shorelines exist. Predictions of the waves generated by typical ski boats for a range of speeds were compared against three different *Wave Wake Rule* curves, each representing different fetch distances. It was demonstrated that activities conducted at the slower speeds, such as wake-boarding, should only be conducted in regions of relatively long fetch (in the order of 1,000 m) if shoreline erosion is to be avoided, or the activities should be conducted at greater distances from the shore (which may not be possible in narrow rivers). Ski boat operation at higher speeds (22 and 30 knots) is less likely to generate damaging waves and thus can be undertaken in more fetch-limited regions.

ACKNOWLEDGEMENTS

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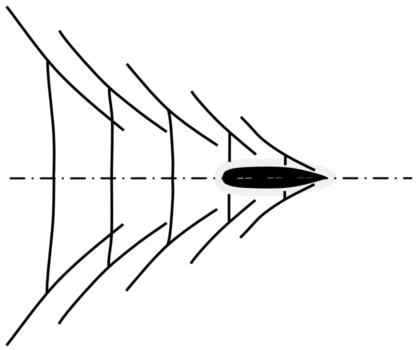
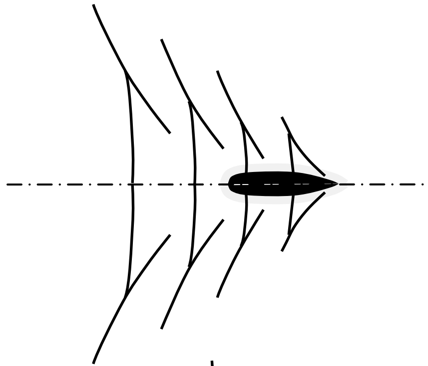
Sub-Critical
$Fr_h < 0.75$

- Short-crested divergent waves
- Transverse waves present
- The well-known Kelvin deep water wave pattern



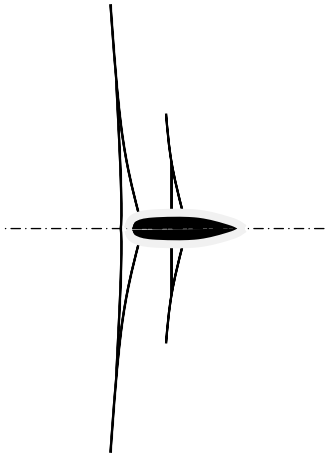
Trans-Critical
$0.75 < Fr_h < 1.0$

- Divergent wave angle increases
- Period of leading waves increases



Critical
$Fr_h = 1.0$

- One or more waves perpendicular to the sailing line
- Crest length grows (laterally) at a rate equal to the vessel speed



Super-Critical
$Fr_h > 1.0$

- No transverse waves
- Long-crested leading waves
- Two or more wave groups having similar periods may exist

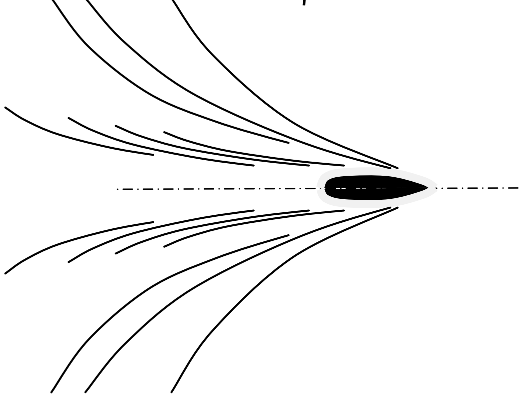


Fig. 1 Simplified depiction of different wave wake patterns for each vessel speed regime

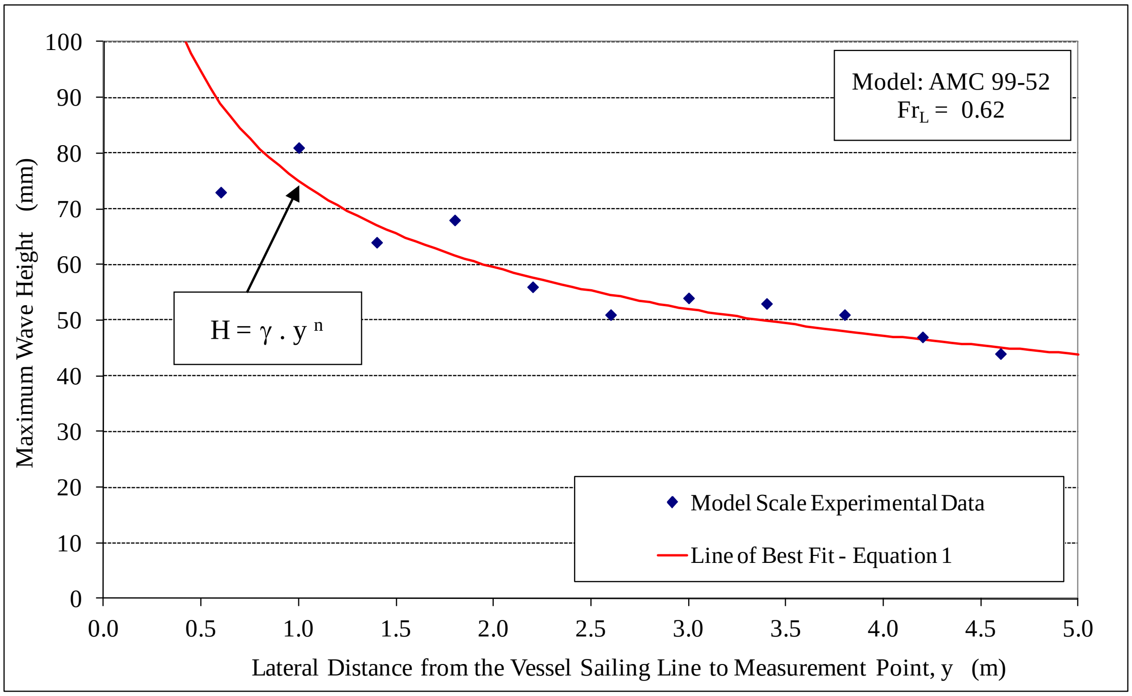


Fig. 2 Wave height as a function of lateral distance from the sailing line

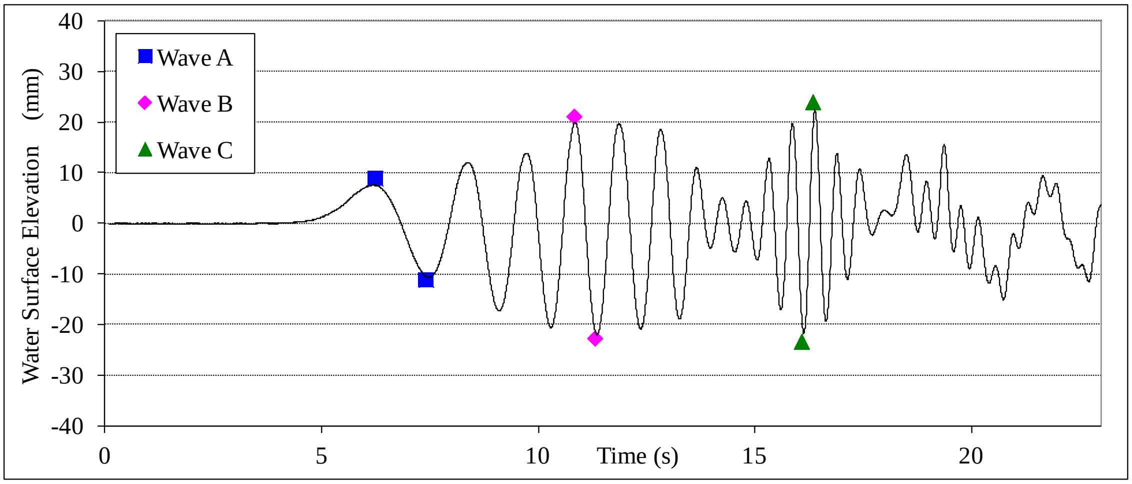
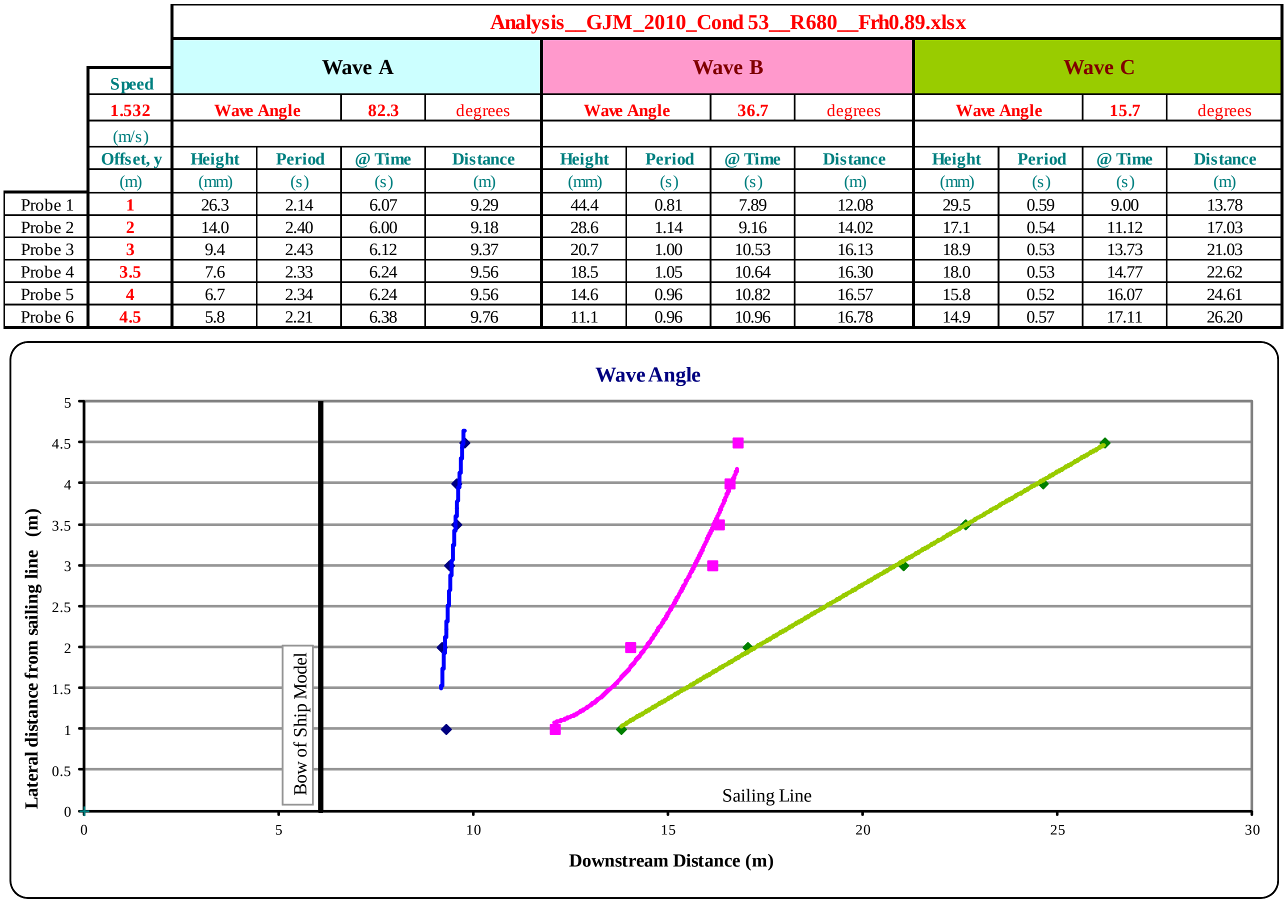


Fig. 3 Example wave profile time series (Waves A, B and C)

	Wave		
	A	B	C
Wave Height (mm)	18.5	43.0	45.0
Wave Period (s)	2.34	0.96	0.52
Wave Energy : proportional to H^2T^2 (J/m)	3.6	3.3	1.1

Table 1 Example wave quantities



		Analysis__GJM_2010_Cond 53__R680__Frh0.89.xlsx											
	Speed	Wave A				Wave B				Wave C			
	1.532	Wave Angle		82.3	degrees	Wave Angle		36.7	degrees	Wave Angle		15.7	degrees
	(m/s)												
	Offset, y	Height	Period	@ Time	Distance	Height	Period	@ Time	Distance	Height	Period	@ Time	Distance
	(m)	(mm)	(s)	(s)	(m)	(mm)	(s)	(s)	(m)	(mm)	(s)	(s)	(m)
Probe 1	1	26.3	2.14	6.07	9.29	44.4	0.81	7.89	12.08	29.5	0.59	9.00	13.78
Probe 2	2	14.0	2.40	6.00	9.18	28.6	1.14	9.16	14.02	17.1	0.54	11.12	17.03
Probe 3	3	9.4	2.43	6.12	9.37	20.7	1.00	10.53	16.13	18.9	0.53	13.73	21.03
Probe 4	3.5	7.6	2.33	6.24	9.56	18.5	1.05	10.64	16.30	18.0	0.53	14.77	22.62
Probe 5	4	6.7	2.34	6.24	9.56	14.6	0.96	10.82	16.57	15.8	0.52	16.07	24.61
Probe 6	4.5	5.8	2.21	6.38	9.76	11.1	0.96	10.96	16.78	14.9	0.57	17.11	26.20

Fig. 4 Example of wave angle analysis

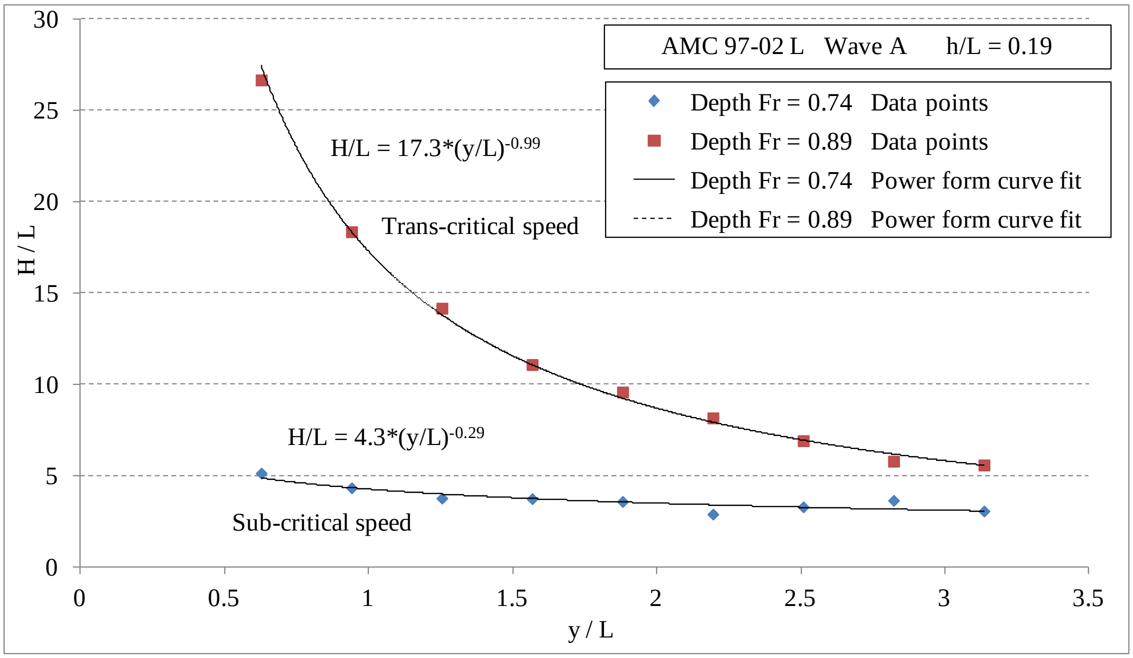


Fig. 5 H/L as a function of y/L: Wave A, h/L = 0.19

Vessel Details	**Symbol**	**Units**
• Monohull or Catamaran		
• Length	L	metres
• Displacement	Δ	tonnes
• Speed	u	knots
Environment Details		
• Water depth	h	metres
• Water density	ρ	kilograms/metre^3
• Lateral distance from vessel sailing line to point of interest	y	metres

Table 2 List of desired input variables for comparison or prediction

	Monohulls		Catamarans	
	Minimum	Maximum	Minimum	Maximum
$L / \nabla^{1/3}$	4.79	11.70	5.26	9.61
Fr_h^*	0.16	2.36	0.16	2.24
Fr_L	0.18	1.34	0.17	1.10
h / L	0.16	2.13^+	0.15	1.76^+
h / d	3.00	78.60^+	3.50	41.50^+

* limits of $Fr_h = f(h/L)$ for each hull
+ considered infinite (deep) water

Table 3 *Wave Wake Predictor*: range of parameters

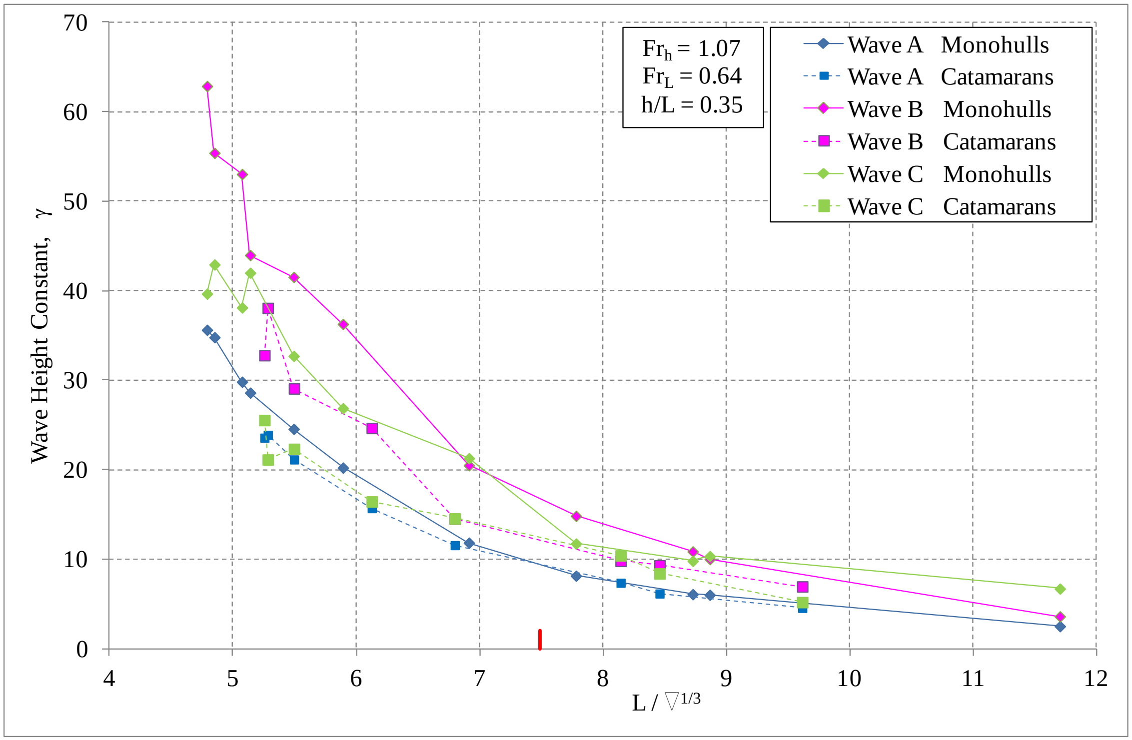


Fig. 6 Example of prediction tool output: γ as a function of L/$\nabla^{1/3}$

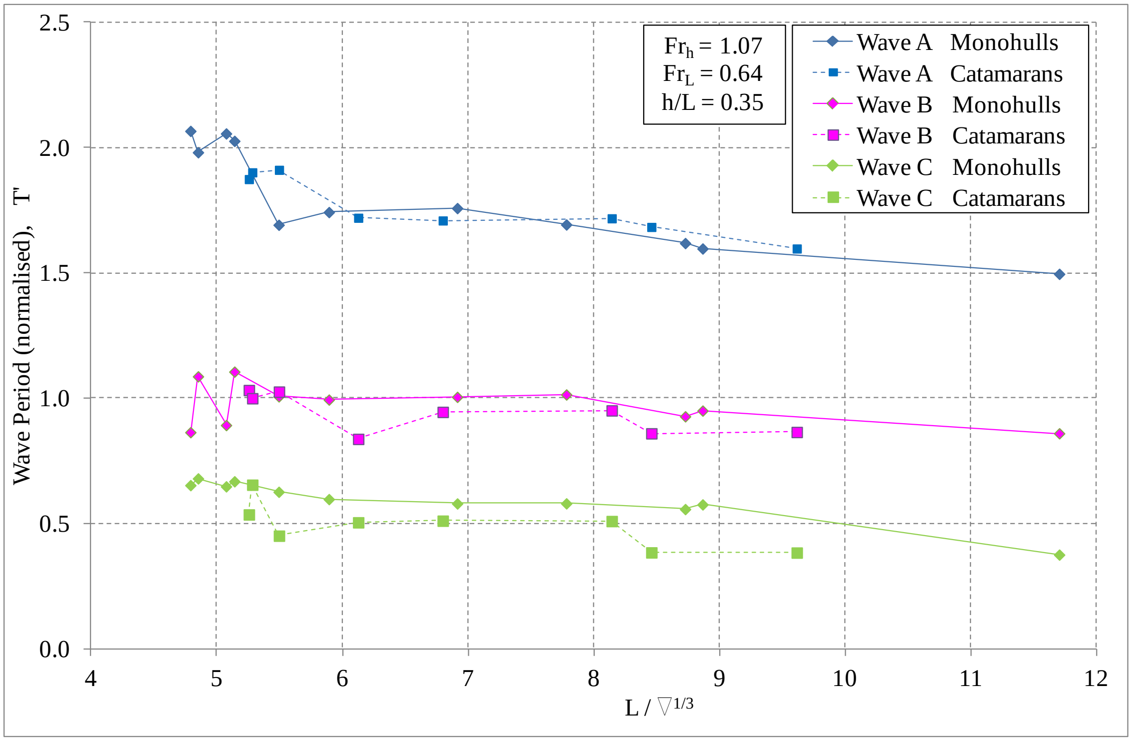


Fig. 7 Example of prediction tool output: T’ as a function of L/$\nabla^{1/3}$

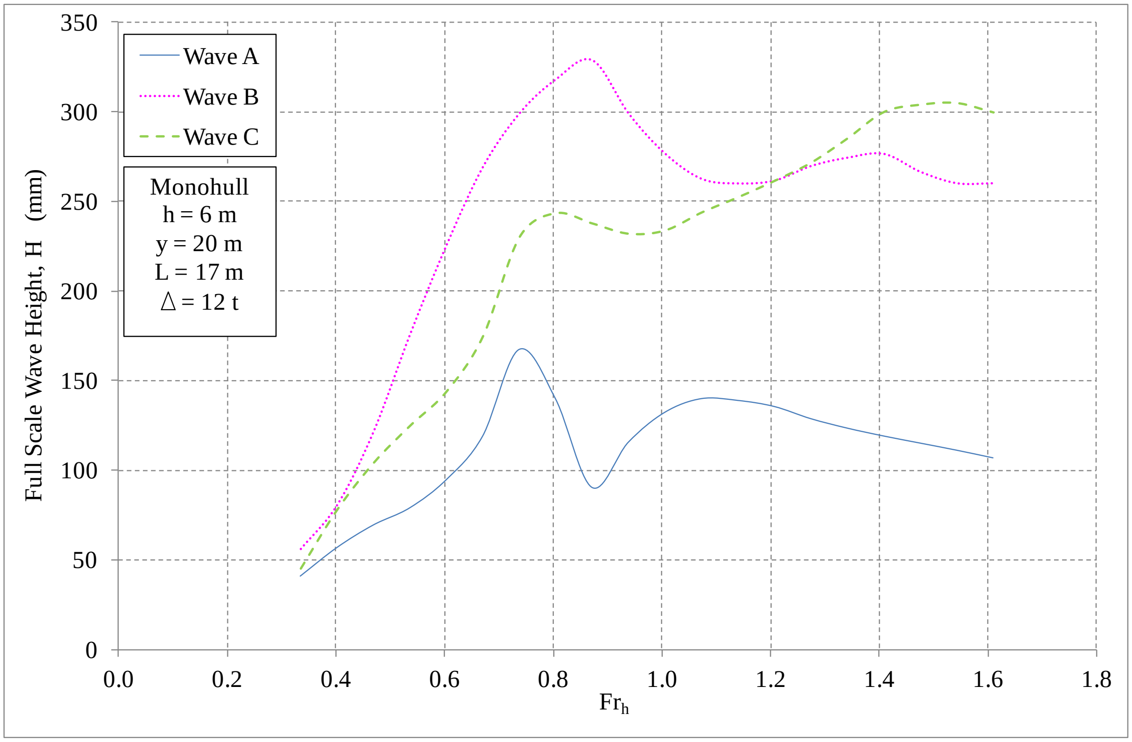


Fig. 8 Example of prediction tool output: H as a function of Fr_h

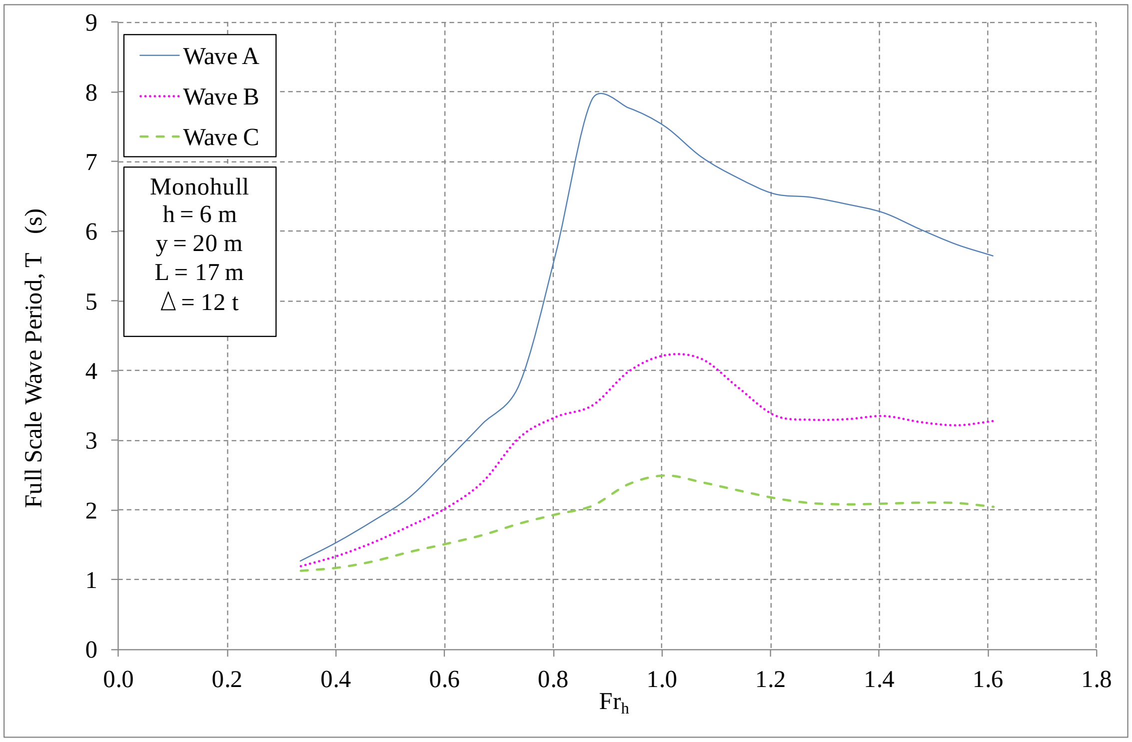


Fig. 9 Example of prediction tool output: T as a function of Fr_h

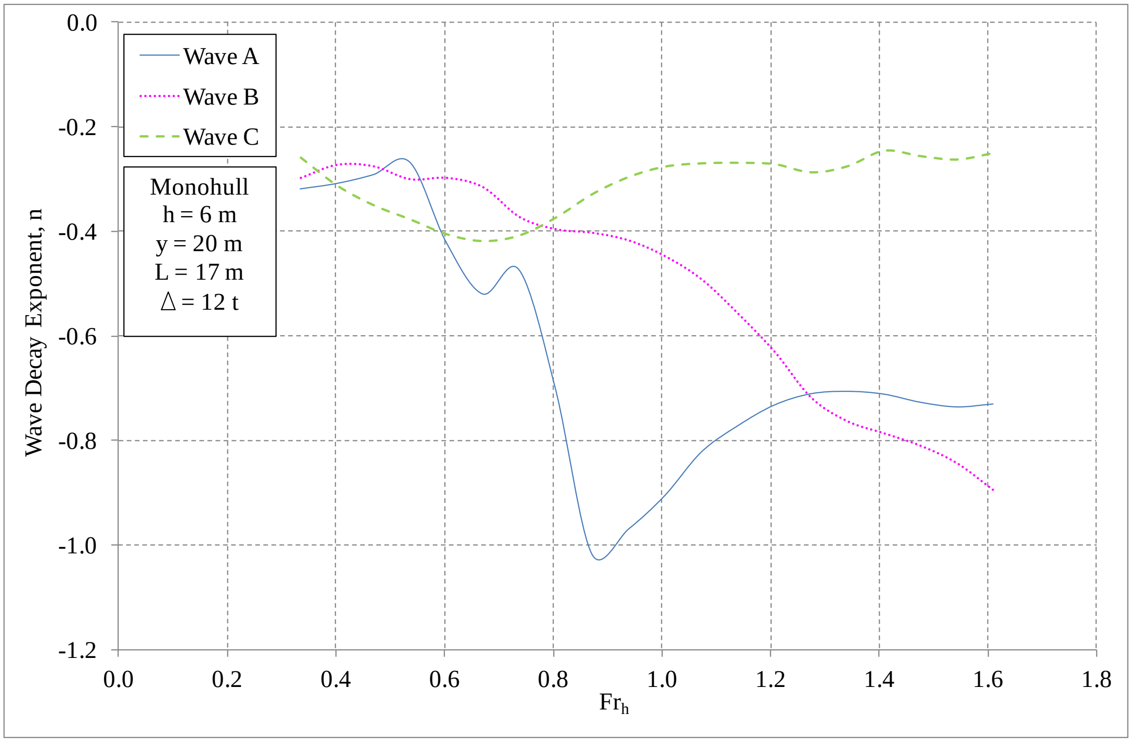


Fig. 10 Example of prediction tool output: n as a function of Fr_h

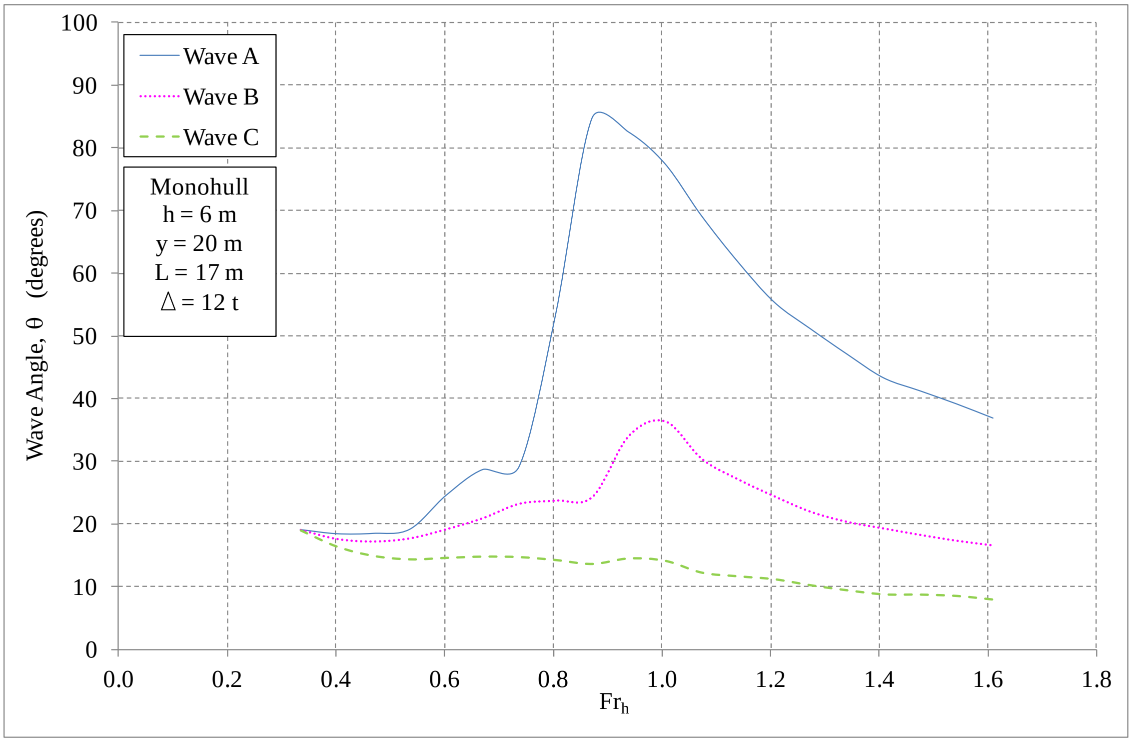


Fig. 11 Example of prediction tool output: θ as a function of Fr_h

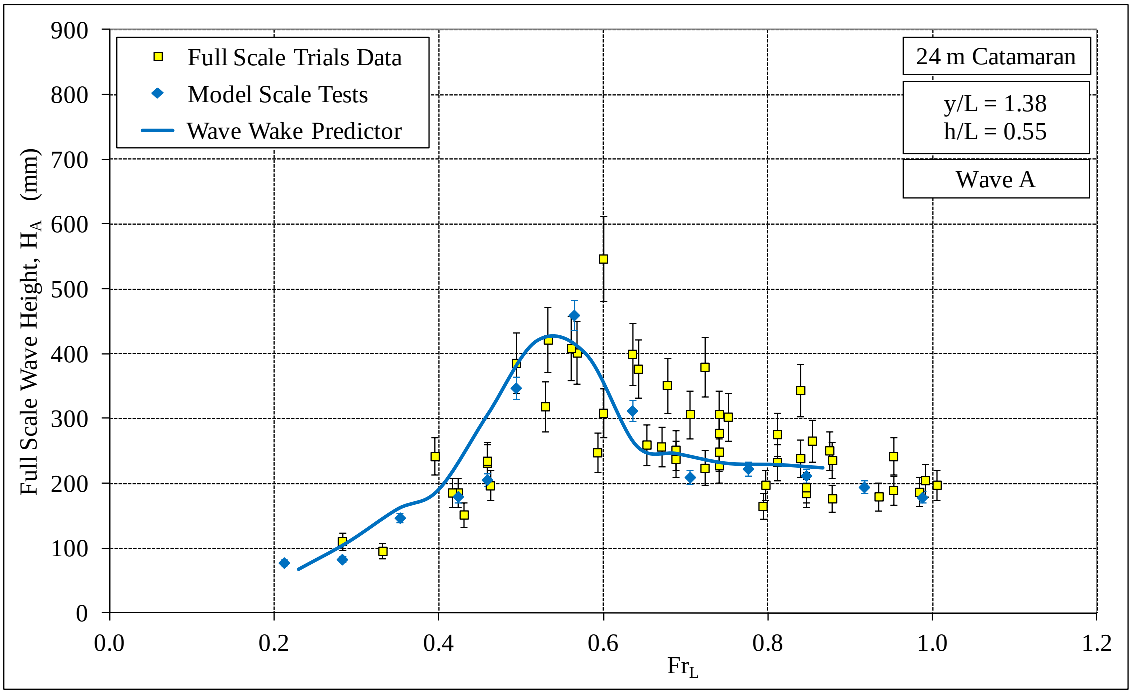


Fig. 12 Validation: 24 m catamaran, Wave A, H_A as a function of Fr_L

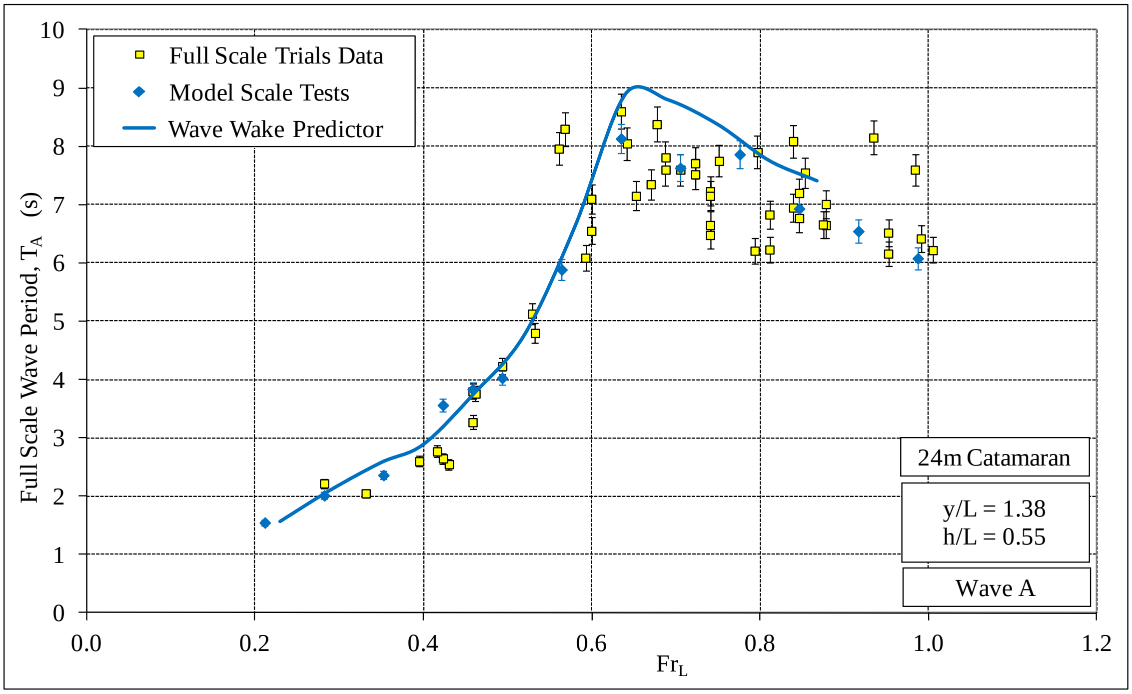


Fig. 13 Validation: 24 m catamaran, Wave A, T_A as a function of Fr_L

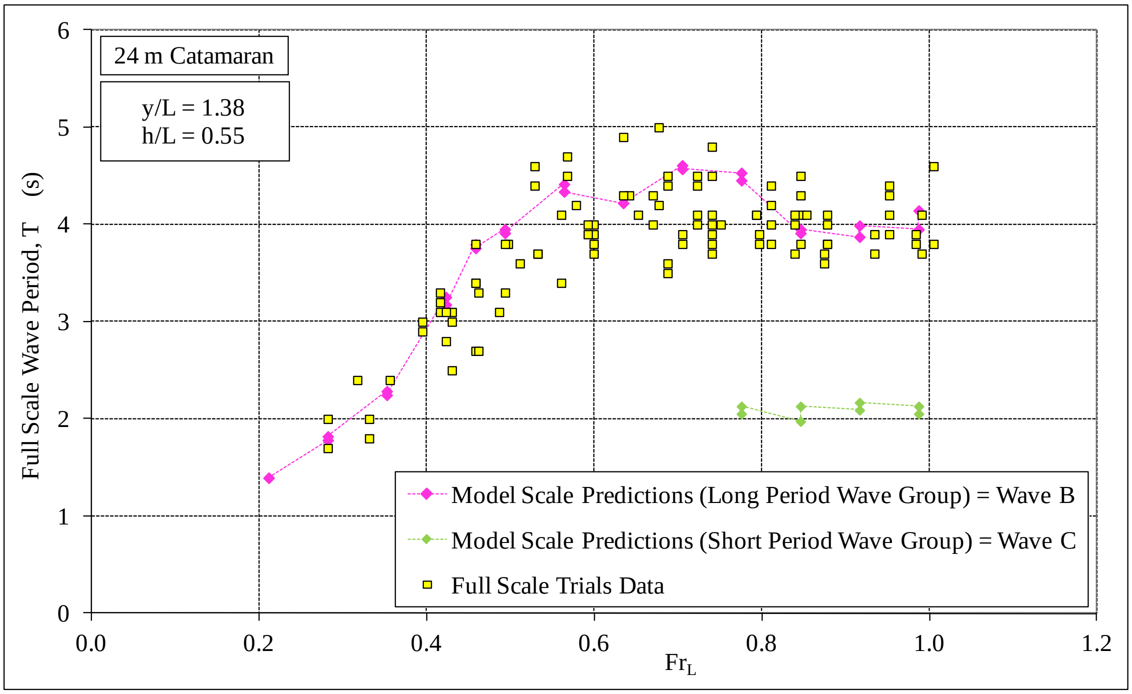


Fig. 14 24 m catamaran, T as a function of Fr_L (from Macfarlane 2009)

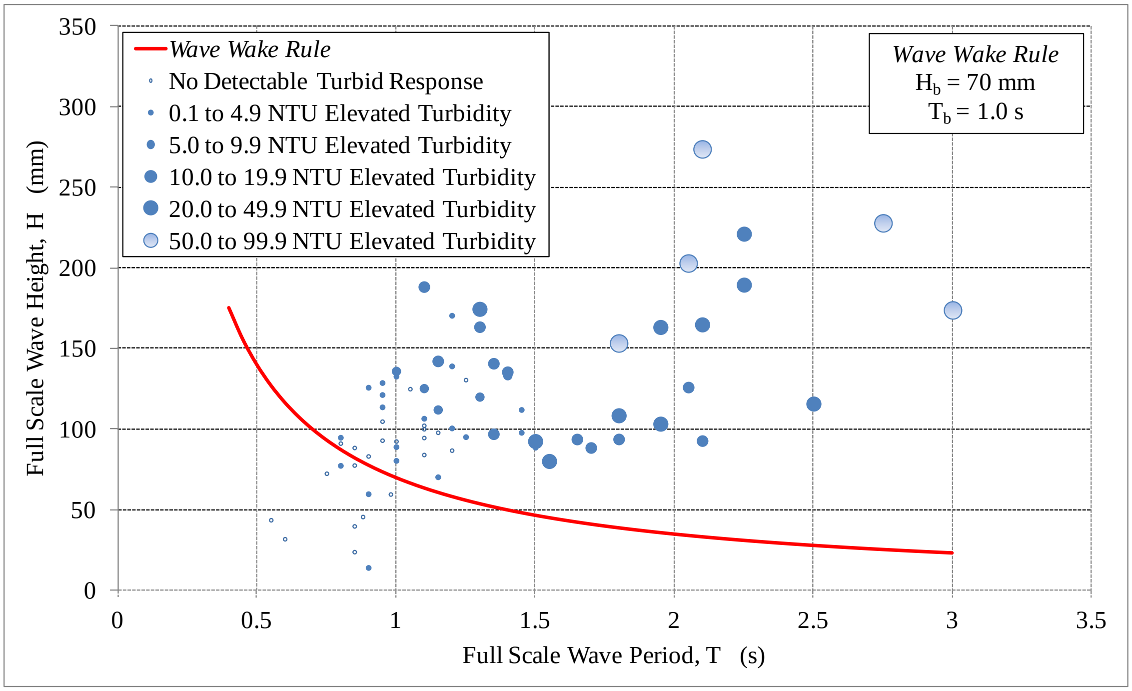


Fig. 15 Measured turbidity used to define *Wave Wake Rule* constants (experimental data from Macfarlane *et al*. 2008)

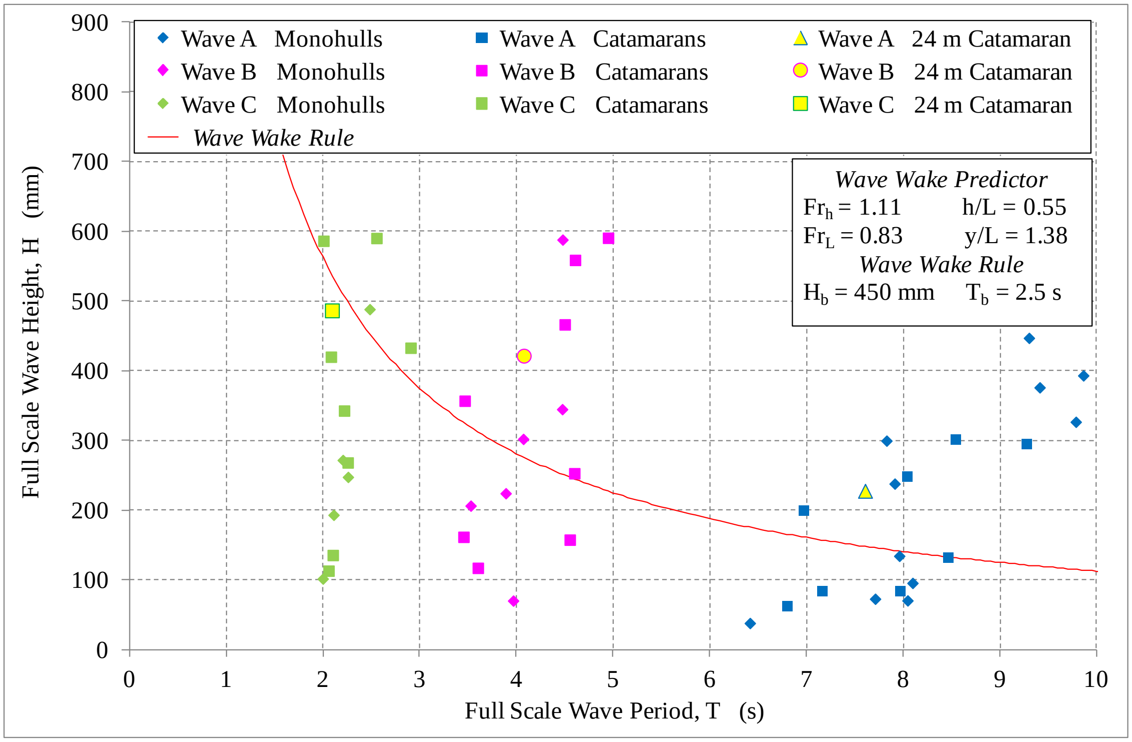


Fig. 16 Example of the combined use of the *Wave Wake Rule* and *Wave Wake Predictor*: 24 m catamaran and other hull forms

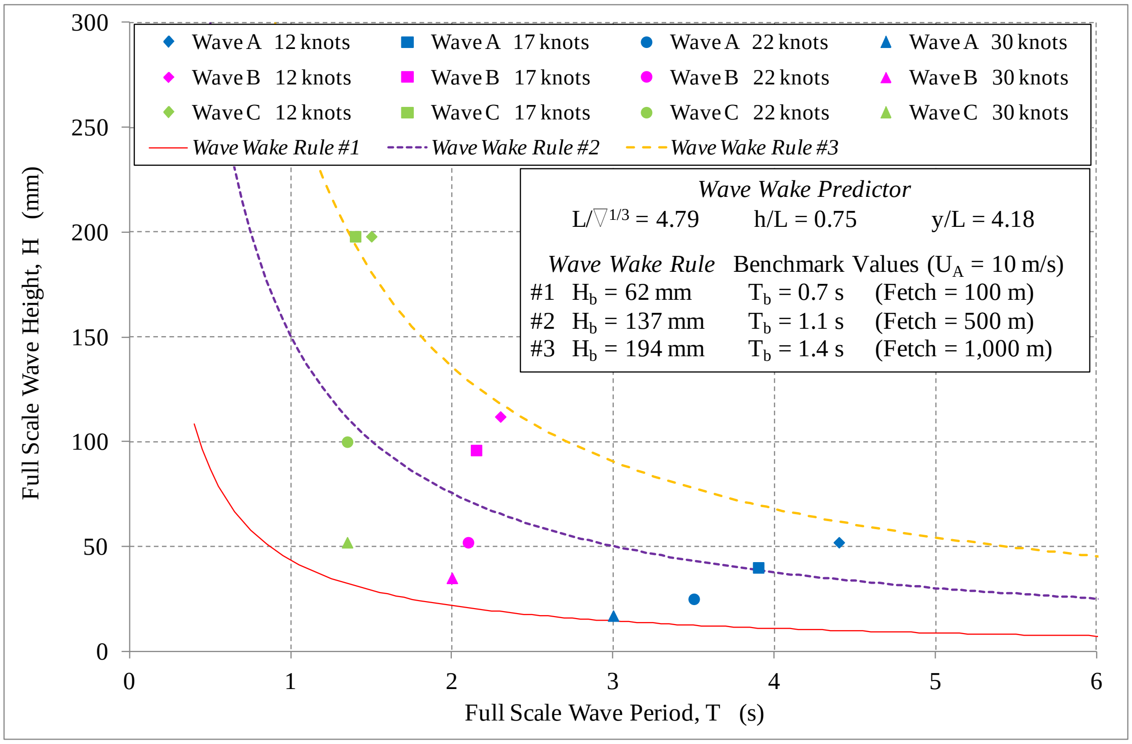


Fig. 17 Example of the combined use of the *Wave Wake Rule* and *Wave Wake Predictor*: ski boats

SNAME-006-2012 Discussion

Alan L. Blume, MSNAME, Blume Maritime, LLC; alan.blume@blumemaritime.com

At the first meeting of the PIANC Maritime Navigation Commission WG 41, which had been established to develop guidelines for managing wake wash from high-speed vessels (PIANC 2003), I told the other members that the guidelines we develop need to make sense to regulators who are not naval architects or experts in hydrodynamics. I think this is a true today as it was over a decade ago. As noted by the authors, the tendency of most efforts to manage wave wake have focused on wave height. No doubt this was in part a result of the amount of adverse impact commonly correlated with the height of a wave – the larger the wave, the greater the damage. It was also a result of the fact that there was experience along many waterways with the wakes of passing vessels as well as storm generated waves that could be used to develop a baseline of what was acceptable wake. As experience with the wave wake from high-speed vessels grew, there has also been an increased realization that although the height of the wave wake from these vessels can be quite low, the wave wake from them was still having adverse impacts due to the energy of the long period leading diverging waves. The work in the current paper is a step forward in the development of a tool that can be used by waterway managers to better manage wave wake from high-speed vessels operating in shallow waters in that it gives consideration to both the highest wave and the longest period wave, i.e., the wave that likely has the greatest energy, in a vessel's entire wave train. The work also seeks to eliminate the impact of site specific factors can have on the accuracy of results by making use of model testing.

The examples provided in the paper illustrate some practical applications of the *Wave Wake Predictor*. However, although it appears to be a tool that can be understood and applied by regulators who are not naval architects or experts in hydrodynamics, there are limitations, which the authors do point out. These include predicting the wave wake of a vessel turning or of a vessel that is speeding up or slowing down. Frankly, these are challenges for any tool attempting to predict a vessels wake. However, based on the challenges experienced by the Washington State Ferries with wave wake along the shores of Rich Passage (Fig. 1) on the route between Seattle and Bremerton, the ability to affectively predict wave wake in turns is a very real need. Similarly, there is a need to be able to predict wave wake when a vessel is speeding up or slowing down – particularly since this most frequently occurs when a vessel is in shallow water when approaching or departing a harbor or terminal.

Lastly, in addition to the challenges identified above, the potential adverse impacts of a vessel's wave wake will vary along the length of the route due to variations in shoreline and how the waterway is used. This can be a challenge since some portions of the route might be more sensitive to wave height, i.e., areas frequented by small vessels, whereas others may be more sensitive to wave energy, i.e., sloping shorelines subject to erosion. The question is whether there is any potential for the *Wave Wake Predictor* to address these challenges.

The PIANC Guidelines attempted to address these challenges as well as the operational factors that can influence wave wake by providing guidance for identifying effective management measures, which include vessel design. The *Wave Wake Predictor* has the potential to determine whether the wave wake from a particular vessel design or type of activity may be acceptable for limiting adverse impacts of wave wake along a particular type of shoreline. However, a question for regulators and vessel operators alike is how, given its current limitations, to use it most effectively as the basis for developing management measures to effectively manage wave wake during the course of a vessel's day-to-day operations.

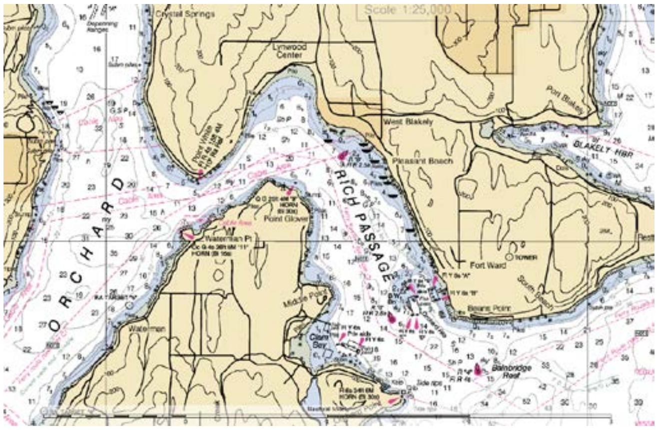


Figure 1: Rich Passage, Puget Sound (NOAA Chart 18474)

Reference

Permanent International Association of Navigation Congresses (PIANC), 2003, "Guidelines for managing wake wash from high-speed vessels", Report of Working Group 41, Maritime Navigation Commission, Brussels.

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The authors are to be congratulated on an excellent, thought-provoking, paper. They have tackled operational matters related to wash nuisance and provided a tool with which wash problems can be studied. They first provide rational definitions of vessel free wave pattern height and identify three key wave groups in the pattern. The first appears to encompass solitary waves which may be shed in the trans-critical conditions, the second suggests the bow wave system while the third appears to relate to the stern wave system. These three groups provide measures of the severity of the wash which are more encompassing than those used elsewhere. The authors then provide a tool – the *Wave Wake Predictor* – which enables heights of the three wave types to be estimated for a given vessel. Finally, they propose a *Wave Wake Rule* which gives a limiting line against which the severity of wave nuisance from the vessel in question can be tested.

Such a detailed paper, while full of interest, leads naturally to a number of questions and comments. Accordingly, the writer considers the authors wave definitions first; these consist of Wave Groups A, B and C. The writer assumes that Wave Group A is of the soliton type, which may or may not appear in the vessel's wave system. Its presence will depend on Froude depth number and water depth/draught ratio and it will be non-dispersive with some mass transport. Consequently its energy will differ from, and be quite significant compared to, that of the free waves in the rest of the vessel wave system. Furthermore, solitons in water are unsteady phenomena, can be shed in multiples and will grow after shedding until they achieve their ultimate height. They also exist as a crest only and may differ in height (and energy content) depending on water depth or Froude depth number and whether the water way is restricted in width or open. As a consequence, accurate determination of their height and period (and therefore nuisance value) in reality might be difficult. Do these considerations affect the use of the *Wave Wake Predictor* or *Wave Wake Rule*?

The writer also assumes that Wave Group C arises from the stern wave system. If so, its form could be determined by hull design and resultant interference effects from the transverse wave system at the sub-critical Froude depth numbers covered by the *Wave Wake Predictor*. The well-known work by the Froudes on hull length and wave interference indicates that stern waves can be modified by changing hull length, suggesting that design could in fact have a part to play in reducing wash nuisance at certain Froude depth numbers. While agreeing with the authors that "small changes to design parameters like waterline beam, draught and angle of entrance are unlikely to turn an erosive design into an acceptable one", would not an increase in length/displacement ratio affect Wave Groups B and C at some Froude depth numbers and provide some benefit from the long slender hulls that would result? If, of course, the authors' statement on design relates primarily to Waves of type A, then the writer is in full agreement, but would be grateful for clarification of their comment.

The authors' work seems to be aimed at what might be termed high speed craft of a certain size and geometry, with their free wave system forming the focus of study. While not criticising this, it is worth mentioning that in some parts of the world – and the United Kingdom is a case in point – waterways with banks vulnerable to wash are used not only by fast craft, but also by slow-moving craft of comparatively significant displacement. These can also erode banks, but the erosion mechanism comes not so much from their free wave system as from their local, or Bernoulli, system, a system avoided by the authors. The drawdown caused by such vessels can be erosive, although, in the writer's experience with mixed traffic waterways, free wave systems from the smaller craft tend to have as much, if not more, erosive effect than drawdown from the larger craft. On some waterways, such as the Suez Canal, while the drawdown from large commercial craft cause erosion which leads to accretion of material in the bed of the canal, the free waves of tugs, moving at higher Froude length numbers, can do physical damage to the upper banks. Can the authors' *Wave Wake Predictor* and *Rule* take such effects into account or are they primarily meant for higher speed vessels such as fast ferries and leisure craft?

Referring to the *Wave Wake Rule*, the authors Equation 2 states the rule applied by Danish authorities; they then introduce their own Rule in Equation 3. This differs from that used in Denmark, but no explanation is given as to why the rule of Equation 3 is preferable to that of Equation 2. By plotting the Danish Rule on Figures 15 and 16 and using the appropriate values of H_b and T_b, similar conclusions to those of the authors in the important discussion in the paper on "*Wave Wake Predictor* and *Wave Wake Rule*" can be drawn. However, there are differences in that, with the Danish Rule, the height of Wave A for the 24m catamaran now falls below the "acceptable" line, that of Wave B remains above the line (and is therefore still unacceptable) and that of Wave C is marginally acceptable. What do the authors feel is the particular advantage of their Rule?

A final small point of discussion arises from the authors' observation that the vessel's propulsion system "is likely to contribute to the height of some of the waves generated". They go on to state that "an increase in height of 10% appears to be a reasonable approximation". This is interesting because it contradicts the received wisdom of one of the components of thrust deduction in a conventional ship wherein the presence of an operating propeller is presumed to reduce the pressures over the aft body, thereby augmenting resistance, or reducing thrust. Does the authors' observation indicate that thrust is in fact augmented by some propulsion systems such a waterjets or is it recognition of squat at the stern indicating an increase in local pressure head?

Overall, the writer feels the paper is an important addition to our understanding of a complex topic which provides a useful tool for the investigation and control of wash nuisance. It will form a valuable addition to the relatively sparse literature on this important subject.

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This paper is significant in that it adopts a broad and systematic approach in a field that has suffered from an abundance of limited case studies and lack of a unified foundation. Sheltered and smooth waters include lakes, rivers and estuaries that are typically very fetch limited, subject to a low energy natural wave climate and have shore landforms that have developed accordingly. Those landforms often consist of geomorphologically recent deposits of unconsolidated sands and muds that are susceptible to erosion by waves with energy in excess of climatic norms. Such energy may be introduced to the geomorphic system by the operation of modern small craft that characteristically have a high ratio of propulsive power to vessel displacement.

An empirically derived scalable *Wave Wake Predictor* valid for a variety of hull forms operating at the range of speed and depth conditions applicable to small craft is long overdue. It appears limited only by the maximum scale speed achievable with the large models used, in that length Froude numbers do not extend to values of 2 or 3 as may be attained by some small planing craft. The online version is expected to become a valuable tool in the management of boat wake on sheltered waterways.

From a geomorphological or bank engineering perspective a critical consideration is the maximum wave and whether or not it is capable of initiating sediment motion. If a maximum wave cannot move sediment then no geomorphic work can occur. In that regard focus upon a maximum wave by various case studies has been entirely reasonable. However the nature of the effective maximum wave may vary, both from site to site and across shore at a single site. Wave driven processes influencing sediment transport and geomorphic change include:

- orbital motion prior to breaking (Komar and Miller 1975);
- breaking, including the transient development of gravity jets, turbulence and air entrapment (Pederson *et al*. 1995, Longo *et al*. 2002);
- swash run up and run down, typified by turbulence, vortices and swash - backwash interaction (Masselink and Hughes 1998, Erikson *et al.* 2005);
- infiltration, exfiltration and groundwater effects (Elfrink and Baldock 2002, Karambas 2006);
- pressure transients (Foda 2003).

Sediment transport due to any of those processes is strongly influenced by wave period (the first three directly, the others indirectly), meaning that simple measure of height alone is grossly inadequate to indicate the sediment transport potential of a wave. To further complicate matters the influence of period also varies with beach slope, affecting breaker type (plunging, spilling or surging) amongst other things. In the presence of river or tidal flow the interaction of currents and waves (Van Rijn *et al.* 1993, Van Rijn and Havinga 1995) must also be considered.

Waves with longer periods have orbital motions extending to greater depth and may be effective agents of geomorphic work upon shoals but break gently if at all upon a steep bank. Higher but shorter waves may cross the same shoal without influencing the bed to break vigorously upon the shore, with consequent geomorphic effect. As relatively long and high waves are both present within any wake the use of multiple waves for wake characterisation appears an unavoidable necessity.

Waves A, B and C
Long period waves are often absent from the natural climate of sheltered waterways and their introduction by navigation may represent a significant geomorphic forcing. In addition to their direct influence, by eroding wave damping shoals long waves may eventually increase the sensitivity of shorelines to attack by shorter period waves (Soomere 2005). As the longest wake waves are typically (but not always) of low amplitude, full scale measurement of maximum period may be confounded by seich, greatly subdued oceanic swell or oscillatory current effects that may influence the 'still' water level even in sheltered waters. The well controlled model tests upon which the *Wave Wake Predictor* is based are therefore a valuable aid to the often difficult task of quantifying 'wave A', that with the longest period.

'Wave B' was defined as the most significant wave following the leading wave and "may not necessarily be either the longest or the highest wave in the wave train". The identification of 'wave B' therefore relies upon expert judgement, fortunately that is handled by the wave wake predictor rather than the user. However it is expected that in many cases where Fr_L and Fr_h are <<1 'wave B' will be both the highest and most energetic, therefore most likely to affect geomorphic work at the waterline.
Later waves in the wake train, such as 'wave C' play an additional geomorphic role. Even if these are incapable of initiating sediment motion themselves they may maintain a suspension of particles eroded by previous waves. Once a particle is set in motion its trajectory becomes influenced by gravity so there is a tendency for material to move downslope and offshore, which may be exacerbated by any transport due to fluvial or estuarine currents. In general, the longer a particle remains suspended the further it is likely to travel.

The wave trace of figure 3 used as definition sketch for waves A, B and C was obtained at supercritical speed. However very similar traces may be recorded at subcritical speed, in which case it appears likely that an analogous 'wave C' would not only be of somewhat smaller amplitude but may represent a transverse wave. These are regarded a lesser bank erosion threat as their period is more likely to resemble those of wind waves, as is their propagation direction in narrow channels.

Other parameters readily calculable by linear theory from digitally sampled wave data might be used to identify significant waves according to site-specific sensitivities. These include maxima of energy, power, orbital velocity at specified depths, breaking depth and run up. However the *Wave Wake Predictor* appears a well-reasoned first approximation tool and in many instances further iterations might not be necessary or within the ready capability of the management authority.

The proposed Wave Wake Rule

This is based upon a Danish wash rule subsequently adopted elsewhere (Parnell and Kofoed-Hansen 2001, Bradbury 2005) but represents a constant energy rather than constant power relation between wave height and period. Curves expressed by the two rules will cross at a point defined by common benchmark values, with the energy rule becoming the stricter with increasing period and reducing height and conversely less strict with shorter period and greater height.

Three methods were suggested by which rule benchmark values might be determined. Method one, simple comparison with the wake of vessels already in service and regarded acceptable, is the easiest but can test neither geomorphic significance of existing practice nor cumulative effect of additions to the wave climate energy budget.

Method 3, hindcasting from wind data, relies upon existence of a record truly representative of the local climate, which in case of sheltered waterways may vary within short distance according to topographic influence upon wind streamlines. Hindcast benchmark values should be chosen to reflect an appropriate time equivalency; marginally above the threshold of erosion only the single maximum wake wave will have any effect. If that wave has a period of five seconds and ten daily vessel passes are expected then a comparable annual wind storm would have duration only slightly greater than five hours.

Expanding upon the Gordon River example used to illustrate method two, experimental geomorphology, figures one and two suggest that in practice it may be difficult determine whether an energy or power based rule is more appropriate. The plots summarise turbidity response of six sites to a total of 583 passes by ten vessels under a range of environmental and operational conditions. Wave energy and power were derived from deep water capacitance probe data sampled at 20 Hz. Both rule lines are necessarily fitted to the most sensitive case of site and water level. Despite the large number of data points the space between the two lines is remarkably unpopulated. Therefore no convincing empirically derived argument can yet be made in favour of either energy or power based rule.

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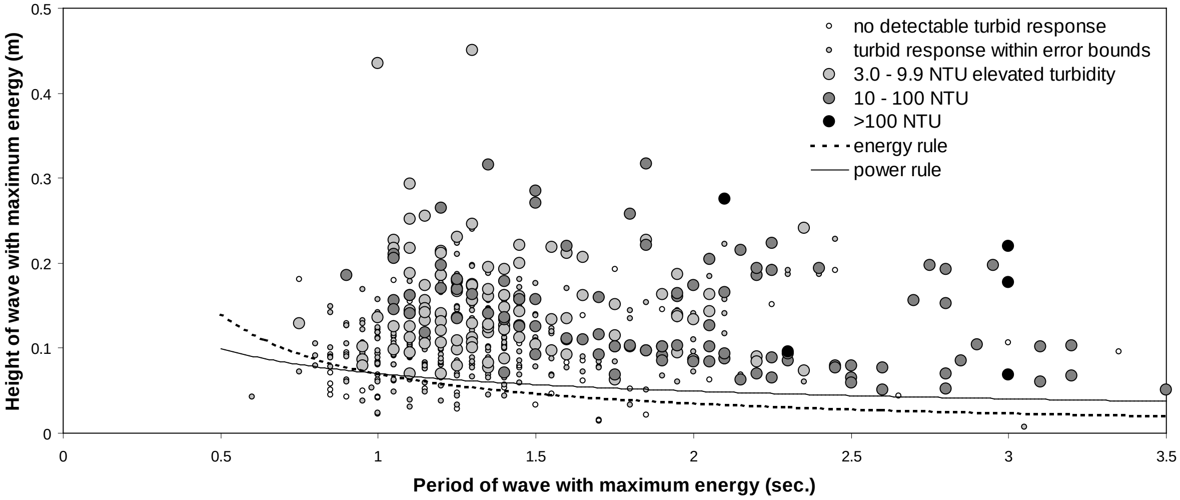

Fig 1: Wave with maximum energy plotted as a function of its height and period and indicated by turbid response of the bank. Lines represent energy and power based rules with common benchmark values of T_b = 1.00 second and H_b = 70 mm (experimental data from Bradbury 2005).

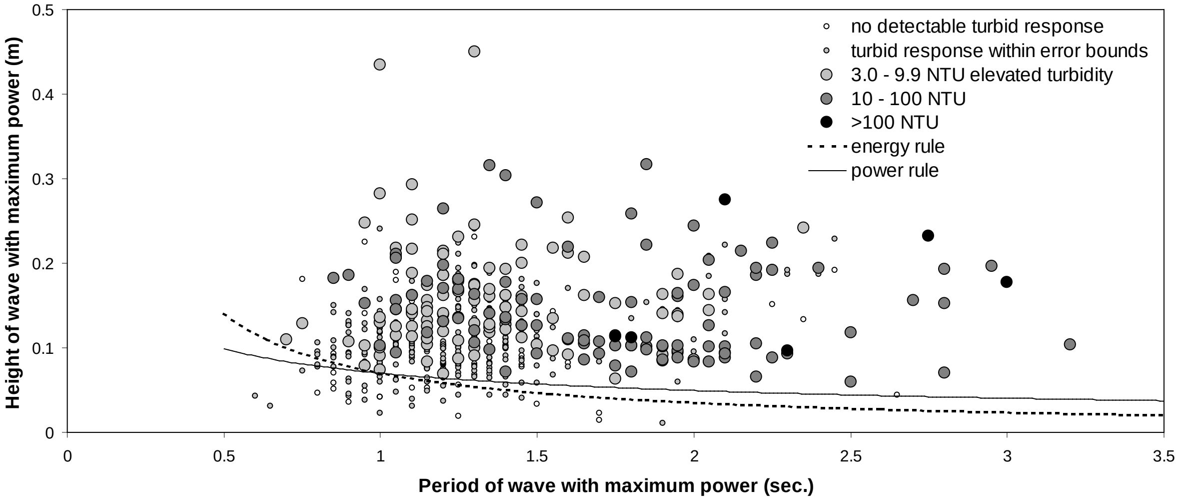

Fig 2: As for fig 1 but the maximum power wave is plotted.

Bruce L. Hutchison, FSNAME, The Glosten Associates. blhutchison@glosten.com

I congratulate the authors on an interesting paper regarding wake wash in sheltered waters with an emphasis on practical perspectives to aid the identification of probable operational perspectives early in design.

I have two lines of commentary. One concerns the methods for predicting wake wash and the author's choices regarding the characterization of wake wash. The other concerns criteria for acceptable wake wash.

Beginning with the prediction methods, it appears that it is based on empirical lookup tables rather than a free-surface potential flow or RANS solver. I have used the free on-line version of the *Wave Wake Predictor* tool to address some real-world problems with which I am familiar, and in every instance I found that my real-world problems fell outside the domain of validity for the *Wave Wake Predictor*. Modern free-surface potential flow or RANS solvers would not share the limitations that the *Wave Wake Predictor* inherits from its empirical database. Furthermore, free-surface potential flow or RANS solvers can be applied to fast vessels with features such as partial foil or air cushion support.

Another advantage of free-surface potential flow or RANS approaches is that it makes possible the identification of the full free-wave spectrum (see, for instance, Heimann, *et al* 2008), rather than just a system of three idealized regular waves. The free-wave spectrum is a complete characterization that can be propagated over distances, and with appropriate coastal engineering tools it can be propagated over bathymetry and shoaled on a beach.

Using methods similar to those found in Kirtley *et al* (2010) I can envision how the *Wave Wake Predictor* could be revised to address the full free-wave spectrum. It is now possible to couple parametrically controlled automated hull model generation with free-surface potential flow (or RANS) solvers and generate thousands or even tens of thousands of hull form/operating condition cases in a reasonable amount of time. Such methods could be used to populate the empirical database of a greatly increased design and operational space, either for the three characteristic waves identified by the authors or for the full free-wave spectrum.

I am uneasy at the implication that there might be any simple universal criteria for acceptable wake wash. The characteristics of beaches and coastlines are too variable to admit such simple universal criteria. Beach morphologies reflect beach (and upland) materials (e.g., grain sizes, density, and much more), ambient wave and current actions, water elevation (possibly subject to tide or river stage), and many other factors. Beach morphologies may change seasonally.

In my opinion the several published criteria for acceptable wake wash are each wedded to the particular environment (e.g., specific locales in Denmark, Australia, New Zealand, and Washington State) where public concern has developed and studies have been performed. The published criteria are, in general, summary criteria for the specific site in question and not directly related to fundamental wave/beach interactions that properly relate wave kinematics and beach properties in engineering terms.

By using the full free wave spectrum it becomes possible to refract the entire wave system over intervening bathymetry and ultimately shoal realistic wave trains on the target beaches. In so doing it becomes possible to estimate fluid dynamic measures such as joint normal and shear stress that can be used by coastal engineers and marine soils specialists to determine the likely impact of the waves on a unique beach structure. I am concerned that the decomposition of the free wave spectrum into three idealized regular waves will not maintain adequate fidelity in ultimate measures such as joint fluid normal and shear stresses on the beach.

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SNAME-006-2012 Authors’ Response to Discussions

We thank Mr Alan Blume, Dr Ian Dand, Mr Jason Bradbury and Mr Bruce Hutchison for their thorough reviews and valuable comments. The ideas expressed in the discussions are very useful in both the interpretation of the results of the study and in shaping our current work.

Alan L. Blume, Blume Maritime

The question is posed whether there is any potential for the *Wave Wake Predictor* to also address the more challenging scenarios when a vessel turns, and when a vessel is accelerating or decelerating.

The Effect of Manoeuvring (Turning)
We agree that the waves generated when vessels turn (or manoeuvre) can be a major contributor to vessel wave wake problems. There do not appear to be many studies that have attempted to quantify this effect, with only generic statements along the lines that the waves are focussed on the inside of a turn and spread on the outside of a turn (Macfarlane and Cox 2004; Schmied *et al*. 2011).
The absolute measurement of wave wake generated during manoeuvring is practically impossible due to the large number of variables involved, such as vessel speed and deceleration during the manoeuvre, rate of turn, steadiness of the turn and change in vessel attitude during the turn (banking, trimming, etc). Then there is the issue of the required location for measuring the generated waves to record what may be regarded as the characteristic manoeuvring wave wake, remembering that it is inevitable that there will be interference from multiple wave trains and the waves will continue to disperse.

The authors have considered these effects for two general categories; the first is for recreational craft such as ski boats, which often engage in highly non-linear tight turns at high speed, and secondly, larger commercial craft that will generally manoeuvre at more constant speeds and in a much wider, more predictable pattern.

Advice given by several ski boat owners is that typical high-speed turns used in water skiing activities (by experienced water skiers) can generally be as tight as 2 to 3 times the waterline length of the vessel.The authors have conducted some full scale experiments which have helped to develop the following general conclusions regarding the waves generated while ski boats manoeuvre:

- The height of the primary waves on the outside of a turn are less than the equivalent straight line condition due to wave spreading, so in general these results are of less interest.
- The waves measured on the inside of a tight turn comprise just those generated continuously during the turn. These waves propagate towards the centre of the turn and will come together at various points inside the vessel sailing line. This will create momentary localised interference and some energy will be dissipated, but the waves will eventually continue to propagate past the sailing line and beyond. The disturbance generated by the turn is therefore localised and the medium to far-field wave energy should dissipate rapidly due to diffraction.
- Once the waves on the inside of a turn pass through their nominal focus point somewhere near the centre of the turn, the waves then diffract as they propagate away from the focus point. A tight turn is therefore potentially more preferable than a wide turn in terms of reducing wave energy that reaches the shoreline.

The authors undertook a series of preliminary scale model experiments from which generally similar conclusions were found for larger vessels undertaking wider turns and at more constant speeds. These experiments involved a rotating arm in a test basin to ensure the sailing line of the ship model was circular and of known radius. A sample of the results from this preliminary study is included in Figure 1.

There was clear evidence that the height of the waves on the inside of the turn were greater than those for the same vessel travelling in a straight line. However, there is the possibility that those waves on the outside of the turn may be at least equal to in height, if not marginally larger than the straight line case. But, these waves should still spread more as they propagate away from the sailing line, thus reducing their likely impact on the surrounding environment.

At this stage, there is no provision within the *Wave Wake Predictor* to directly predict the effects when a vessel turns, however it is hoped that a continuation of the study described above will allow this to be possible in the future.

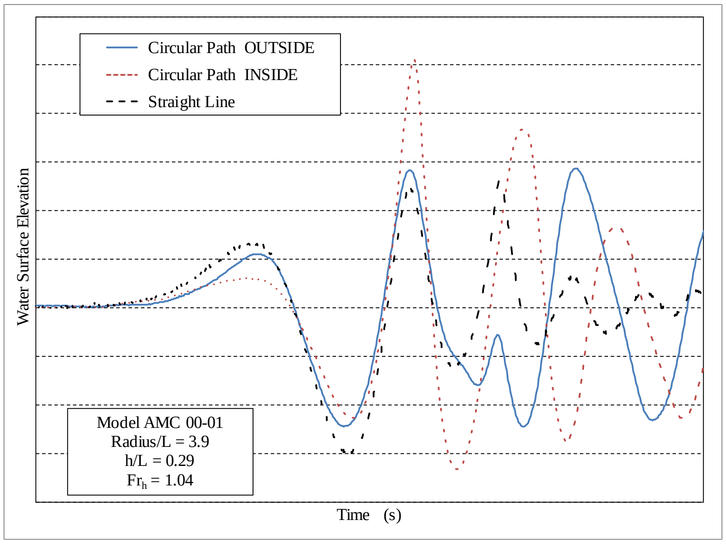

Figure 1 Comparison of wave profiles of vessel with circular and straight paths

Acceleration and Deceleration
As the discusser has quite rightly indicated, as any boat accelerates or decelerates through the various speed regimes it will obviously pass through those zones when larger, more damaging waves may be created – particularly when this transition in speed occurs in shallower water and close to busier regions such as a harbor or terminal. The result described by Torsvik *et al.* (2006) is of relevance here, as they found that it is possible to almost avoid generation of high waves for accelerating ships, but virtually impossible when a ship's speed decreases from a super-critical to sub-critical speed (relative to depth). For accelerating ships it was found that the amplitude of the solitary wave generated is highly dependent on the transition time, with a fast transition the best way to avoid the generation of these unwanted waves.

The wave wake predictor is capable of predicting the likely worst-case waves when a vessel accelerates or decelerates. This is a relatively straight-forward process using the full version of the tool held at AMC, but could be achieved using the basic online version currently available, provided a systematic approach is undertaken (but it may be time-consuming).

Varying Conditions along a Route
Mr Blume also asked if the predictor can deal with scenarios where the type of shoreline and the use of the waterway varies along a vessel route. It is not uncommon for a vessel route to encounter regions that are more sensitive to specific characteristics of vessel generated waves than others. Any route planning process should identify these potential concerns as part of an environmental impact study. The characteristics of 'acceptable' waves need to be determined for each these regions/activities – the *benchmark* wave height and period referred to in the paper.

The *Wave Wake Predictor* and the *Wave Wake Rule* are ideal tools in such scenarios as they can be used to very quickly identify if any potentially damaging or dangerous situations are likely to arise for any generic vessel design, and if so these tools can be used to undertake a more in-depth study to find what remedial actions, such as altering speed or route, can be undertaken and whether these actions will be adequate to avoid any issues.

Dr Ian Dand, BMT Isis Ltd

Wave Definitions
Dr Dand quite rightly states that waves of soliton type may be generated at trans-critical depth Froude numbers and that their nuisance value can be extremely high.

From the outset of this project, it was not the intention to develop a prediction tool with the ability to precisely predict the characteristics of such complex, unsteady phenomena that occur within this relatively narrow range of depth Froude numbers as a vessel approaches the critical speed. The primary purpose of the *Wave Wake Predictor* is to provide reliable predictions at more practical speeds of operation – generally either at sub-critical or super-critical speeds. Predictions within the trans-critical range are also provided, and they should be generally representative of the actual waves generated, but it will not specifically identify if any of these are of soliton type (and hence, unsteady in nature).

Any vessel operator, or user of the *Wave Wake Predictor*, should be fully aware when the combination of vessel speed and water depth puts them in this region of concern. Therefore, a suitable warning has been built into the Input Worksheet of the *Wave Wake Predictor* when this occurs.The warning consists of a text message, indicating that the desired combination of speed and water depth has resulted in a trans-critical speed. In addition, the appropriate cells change colour -for low trans-critical speeds (starting at Fr_h = 0.75) the cells change from white to a light red. This red becomes more vibrant as Fr_h approaches unity.

Effect of Vessel Design on Waves A, B and C

Our statement that “small changes to design parameters like waterline beam, draught and angle of entrance are unlikely to turn an erosive design into an acceptable one” refers generally to vessels that operate in semi-sheltered regions (rather than sheltered waterways possessing very sensitive banks). In cases with more exposed shorelines, energy states tend to jump in orders of magnitude, not in incremental percentages. Thus, changes to hull form – that generally don’t alter the displacement of the craft – will not change the vessels potential to cause bank erosion.

We fully agree with Dr Dand that an increase in length/displacement ratio (i.e. longer, slender hulls) will provide benefits, not just for Waves B and C, but also Wave A – as is highlighted in Figure 6 in our paper, where wave height clearly reduces with an increase in this ‘slenderness ratio’.

Bernoulli Waves in Canals of Restricted Width

As outlined in our paper, the series of experiments from which the *Wave Wake Predictor* was developed deliberately covered a wide range of vessel speeds, water depths and different hull forms (with slenderness ratios ranging from 4.8 to 11.7). The intention was to “cover all practical bases”,thus the tool is certainly capable of predicting the characteristics of the free wave system for a wide range of speeds and hull forms – not just fast ferries and leisure craft.

However, it has not included large full-form vessels where the most significant waves generated are of Bernoulli type. The authors agree with Dr Dand that the drawdown caused by such vessels can, and has caused, significant bank erosion, particularly in cases where blockage plays a significant role (where the waterway is restricted in both width and depth). This is an area of interest to the authors and, with further work, may result in a future capability of the prediction tool.

Wave Wake Rule

Dr Dand asks what we feel is the particular advantage of our *Wave Wake Rule* over the Danish wash rule. As he has indicated, the curves provided by the two rules (in plots such as those shown in Figures 15 and 16) will be similar when based upon common benchmark values (they will cross at a point defined by these values). The important difference between the two rules is that our *Wave Wake Rule* becomes stricter with increasing wave period, by reducing the allowable wave height, and conversely less strict with shorter period.

The authors have assessed bank erosion due to vessel generated waves in many Australian rivers, including the Gordon, Brisbane, Noosa, Bremer, Maroochy, Mary, Parramatta, Canning and Swan Rivers. We have concluded that in this type of waterway, and the type of marine craft involved (typically small commercial vessels and recreational craft) it is the higher period waves that are of most concern.

The Danish wash rule is commonly applied when large high-speed craft operate in coastal regions, whereas we suggest that the *Wave Wake Rule*, because of its stricter control of wave period, may be better suited to more sheltered waterways such as rivers and estuaries.

Effect from Propulsion System

Dr Dand has posed a question about the effect of the propulsion system on the vessel wave wake. This was not quantified by the authors, but has been considered by several other researchers. For example, Taato *et al*. (1998) conducted an experimental study to investigate the effect that both conventional propellers and water-jets have on the height of the wave wake generated by a generic high speed monohull. Their model tests considered three cases: towed, self-propelled by water-jets and self-propelled by propellers. They concluded that the propulsion systems do not change the general pattern of waves generated, however both propulsion methods may cause an increase in wave amplitude. For example, conventional propellers may cause a 5-10% increase in wave height as compared to the towed case. This is in general agreement with Leer-Andersen and Lundgren (2001) who conducted both towed and self-propelled (using propellers) scale model experiments on a high-speed catamaran operating in both deep and finite water depths. Leer-Andersen and Lundgren also concluded that this increase in wave height may be affected by water depth, with the increase in height being greater the shallower the water depth.

Taato *et al*. (1998) also claim that an increase in wave height of between 20-40% may be expected when the same monohull model is self-propelled using water-jet units. This is a considerably greater increase than the findings of Werenskiold and Stansberg (2011) who conducted scale model experiments on a catamaran, both towed and self-propelled using two stock water-jet units. Werenskiold and Stansberg found an increase in (maximum) wave height of up to 10% for the model propelled by water-jets. The authors assumed that the difference between their towed and water-jet propelled models were due to known differences in trim of each model.

The large increase in height found by Taato *et al.* for their water-jet propelled model is potentially due to experimental error and/or changes in dynamic trim, when compared to the towed ship model. To investigate this further, it is useful to review the time histories of the wave profiles presented by Taato *et al.* where it is evident that the amplitude of almost all waves for the water-jet case, including the leading waves, are higher than the towed model case. In the author's view, it is unlikely that the propulsion system alone will affect all waves in the wave train in a similar manner. It may be more likely that the effect of the propulsors on the leading (bow) waves may be minimal, given that the propulsion system is usually located well aft in most vessels. For the leading waves to have also been affected suggests that it is likely that something else has changed, such as a significant difference in running trim, and/or experimental error, to result in such large differences in wave height.

In summary, it is generally accepted that a vessel's propulsion system, regardless of type, may affect the waves generated. However, further research may be required to answer Dr Dand's specific question.

Jason Bradbury, Tasmanian Department of Primary Industries, Parks, Water and Environment.

The authors thank Mr Bradbury for his very kind and useful comments. Although he has not raised any specific questions, we would like to add some further background on the use of our *Wave Wake Rule*.

Mr Bradbury presents data from turbidity experiments (his Figures 1 and 2) which show the respective curves for the Danish wash rule and our *Wave Wake Rule* – it can be concluded that very little difference exists between the two, as Mr Bradbury points out. In this case we strongly support the use of either rule as both present a significant improvement over now outdated regulatory criteria based solely on wave height (thus ignoring wave period). It should be noted that the data presented is for the specific case of the remote Gordon River in a World Heritage Area where the river banks are very steep and sensitive to erosion, and is exposed to a very limited range of vessel types and speeds. This is reflected in the very low benchmark values of height and period (H=70 mm, T=1.0 s) that have been adopted for regulating vessel operations (very successfully) over the past seven years.

We believe the *Wave Wake Rule*, with its stricter control of wave period, is a more appropriate regulatory criterion for busier sheltered waterways, such as rivers and estuaries around populated areas, where there is a much broader range of shoreline types, water depths, waterway widths, and vessel types and activities. Subsequently, the range of appropriate benchmark values is much greater, but still relatively small compared to those that may be adopted for large high-speed craft operating in coastal regions.

Bruce Hutchison, The Glosten Associates.

Mr Hutchison is correct that the *Wave Wake Predictor* is based on empirical lookup tables generated from the analysis of a comprehensive series of physical scale model experiments, rather than a free-surface potential flow or RANS solver. We have previously adopted similar numerical techniques to predict vessel wave wake, however we have experienced varying degrees of success when it came to validating these predictions against model and full scale trials data. This was particularly the case for vessel operations in finite-water depth in the trans-critical speed regime and for some hull forms. As a result, we were more confident of achieving realistic predictions by developing the prediction tool based on an experimental rather than numerical approach. It also helped that an ideal test facility for this sort of work, and a wide range of existing scale models, were both readily available to us.

Although the range of applicability of the *Wave Wake Predictor* is relatively wide in terms of vessel type, speed and water depth, as the discusser has found it does have limitations. We would be greatly appreciative if the discusser, and any other users of the online version of the tool, would please inform us of the limiting factors they experience for their real-life scenarios. This will allow us to prioritize our future work to increase the applicability of the tool.

Some of the existing limits have already been extended on the full version of the tool held at AMC by extrapolating beyond the maximum speed achieved in the model tests. For example, Figure 2 shows that our full scale trials data for several ski boats has allowed us to significantly extend the range of applicability, from a length Froude number of approximately 1.3 up to 2.2. Similar improvements are also underway where other relevant and reliable data is available.

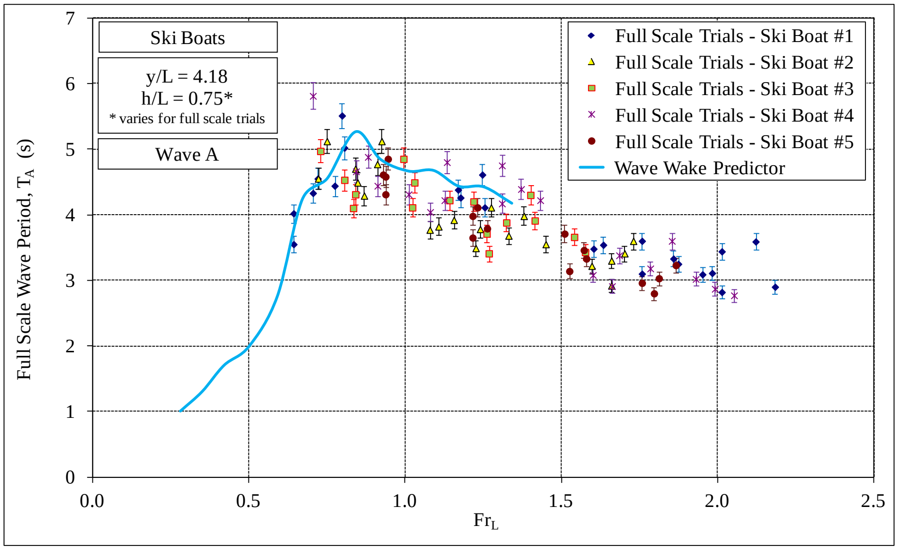

Figure 2 Example of full scale trials data used to extend the limits of applicability

As Mr Hutchison has quite rightly stated, there are occasions where knowledge of the full free-wave spectrum is desirable or required, and in such cases the use of numerical techniques may be ideal. However, one of the primary motivations for developing the *Wave Wake Predictor* was to provide a means of rapidly and accurately determining if a vessel of known basic parameters meets or exceeds a specific regulatory criterion. We have never come across any situations where the full free-wave spectrum has been required for this purpose – in all cases only very minimal data about the generated waves is required to make such an assessment, typically just the wave height and period of a (single) representative wave at a single lateral distance from the vessel's sailing line (at each speed).

We fully agree with Mr Hutchison that there is no simple universal criterion for determining acceptable wave wake. The most commonly adopted criteria (Danish Wash Rule, Washington State Ferries, etc) can readily be applied where the shoreline characteristics vary dramatically. Regardless of which regulatory criterion is adopted, the most crucial step is the determination of the appropriate limits for the criteria (or 'benchmark values' in the case of our *Wave Wake Rule*) that are applied in each specific scenario. Once again we refer to our Gordon River example, where different benchmark values are applied to different zones of this river – each zone has been classified by its shoreline properties (i.e. one zone has cohesive mud banks, another has sandy levee banks).

The numerical methods described by Mr Hutchison may be very useful in determining the various benchmark values that would be appropriate along a proposed vessel route where the shore characteristics vary. Generating the full free-wave spectrum, and investigating how this changes as the waves propagate over intervening bathymetry and shoal on the target shoreline would provide useful data to identify limiting conditions, particularly for very localized conditions.

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